# Status of the experimental campaign: NuBall2+PARIS+SiLCA at ALTO

Katarzyna Hadyńska-Klęk and Jonathan Wilson

On behalf of the NuBall2+SiLCA(DSSD)+PARIS collaboration

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Accélérateur Linéaire auprès du Tandem d'Orsay

HIL
Heavy Ion Laboratory

COPIN IN2P3 Workshop 2023

**COPIN: 23-156**

# ν-Ball2: Scientific goals

- To perform hybrid γ-ray spectroscopy of neutron-induced, particle-induced and spontaneous fission
- To facilitate innovative experiments (e.g. Coulex, nuclear moments, lifetimes, GDR studies, etc.)

ν-Ball2 aims for full exploitation of ALTO's key strengths:

- ✓ High-flux directional neutron beams
- ✓ Rare stable beams
- ✓ Capacity to handle radioactive actinide targets
- ✓ Generic FASTER DAQ (easy coupling of different detection systems)
- ✓ Culture of innovation
- ✓ "Hands on" experiments in an enjoyable and stimulating environment

# ν-Ball2: Technical/logistical Objectives

Bringing together equipment to the ALTO facility from different labs in Europe

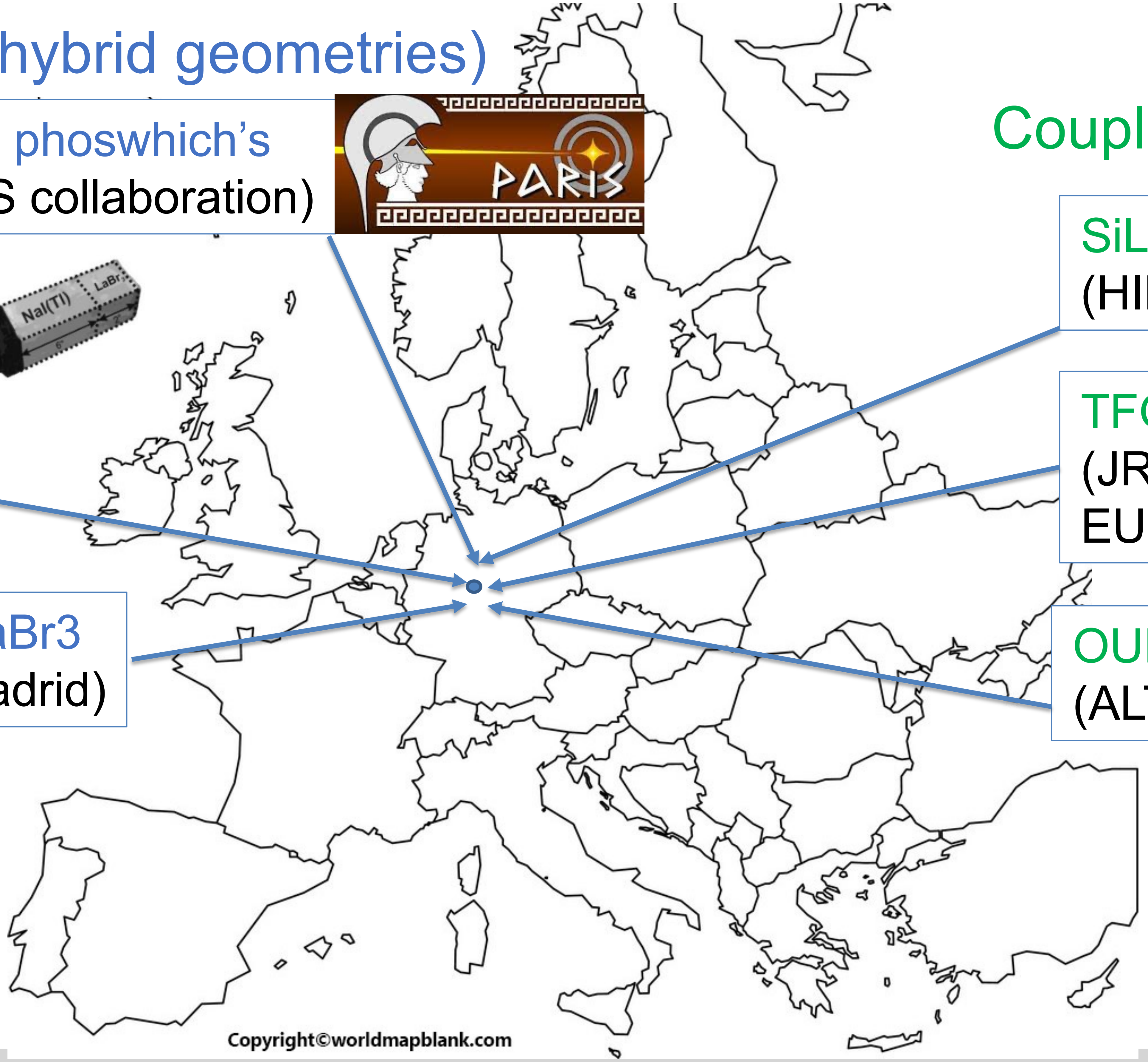
## γ-detectors (3 different hybrid geometries)

Clover Ge's
(Gammapool
EU consortium)

Co-axial Ge's
(loan pool)

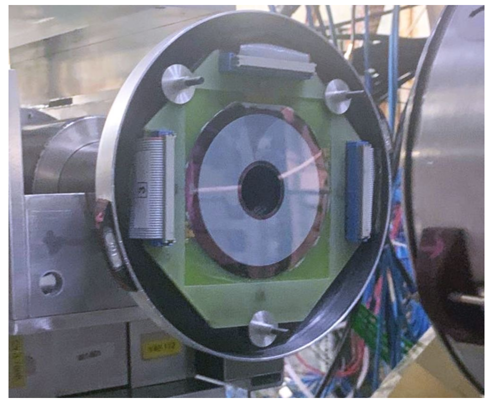
PARIS phoswhich's
(PARIS collaboration)


FATIMA LaBr3
(Surrey/Madrid)

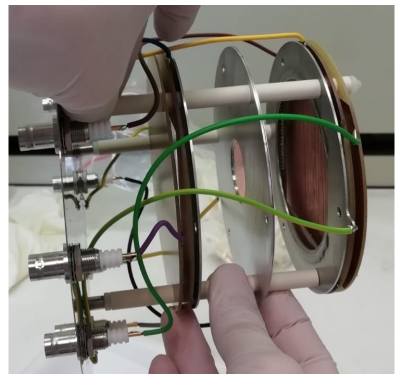



## Coupled Devices

SiLCA DSSD
(HIL Warsaw)



TFGIC
(JRC-Geel
EU commission)



OUPS Plunger
(ALTO/IJC Lab)

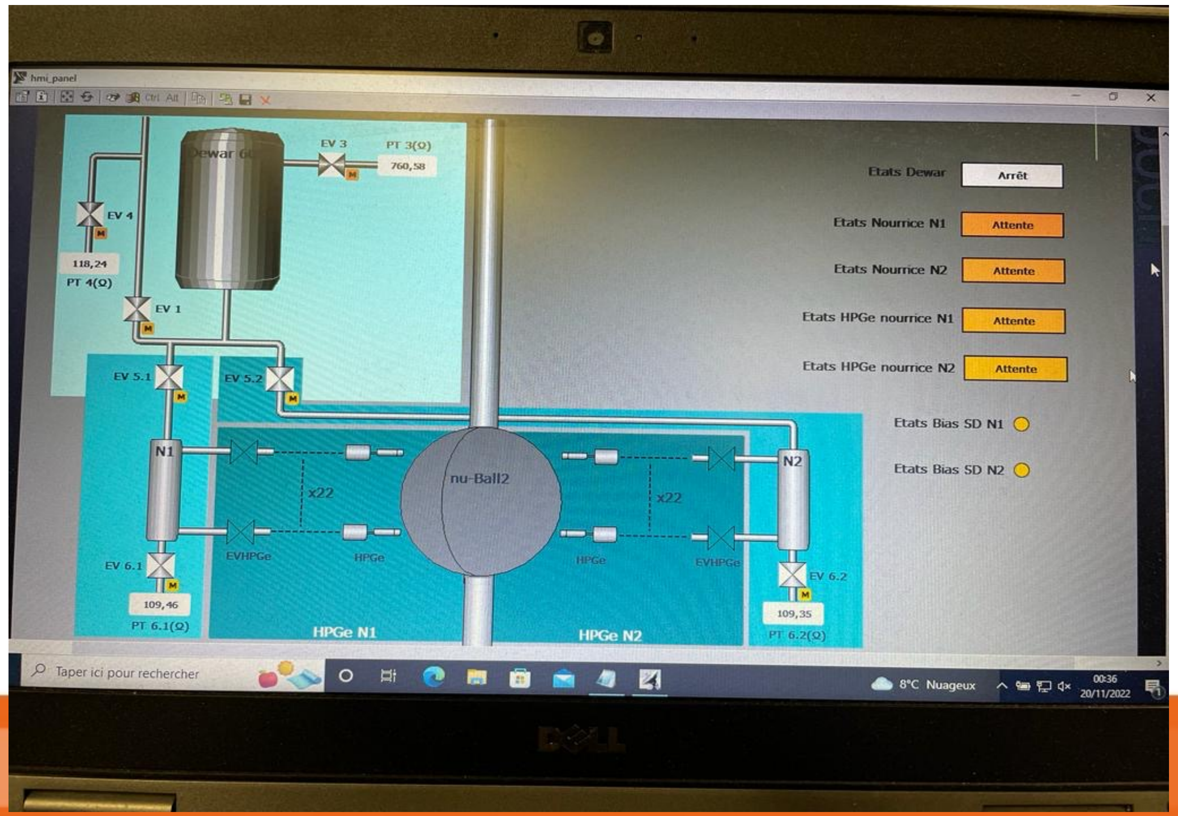
LICORNE
(ALTO/IJC Lab)

OPSA CP detector
(ALTO/IJC Lab)

NuBall 2

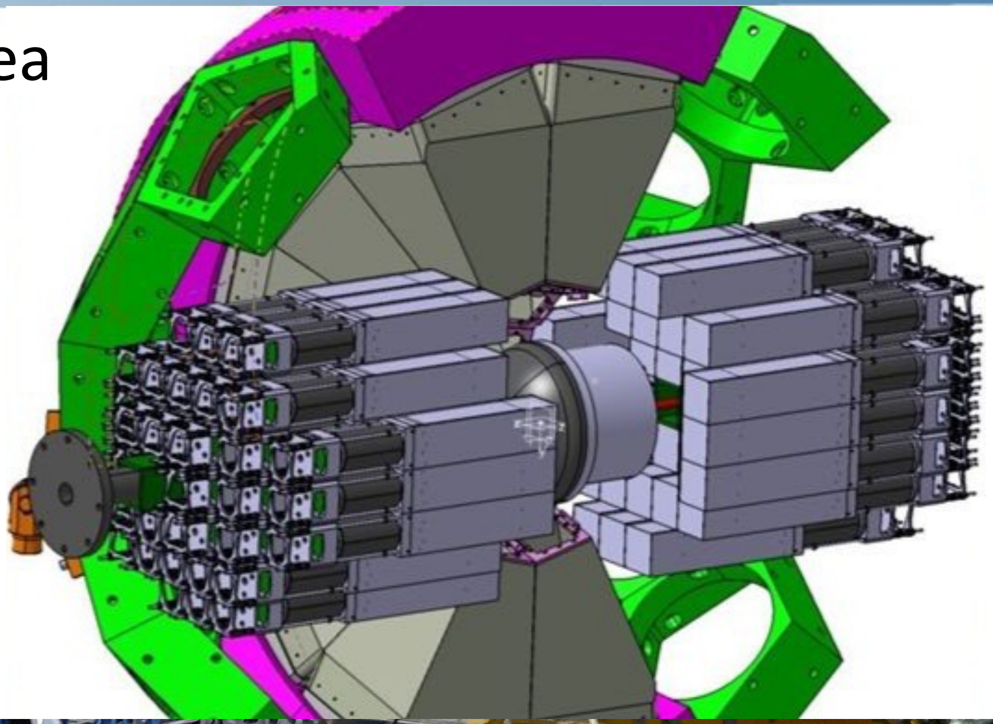
# nu-Ball2 Construction and commissioning phase

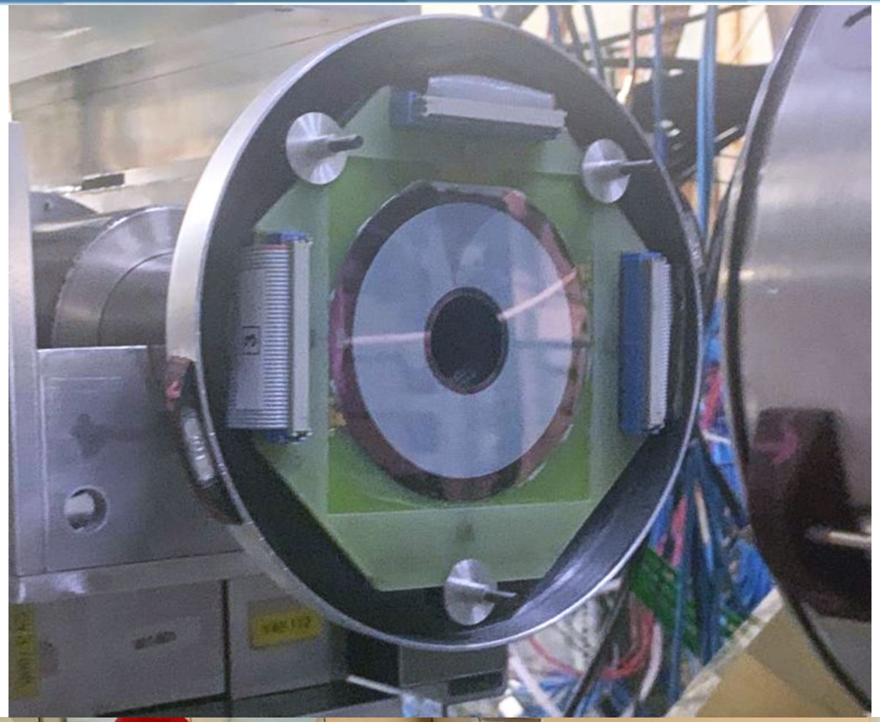
January – March 2020



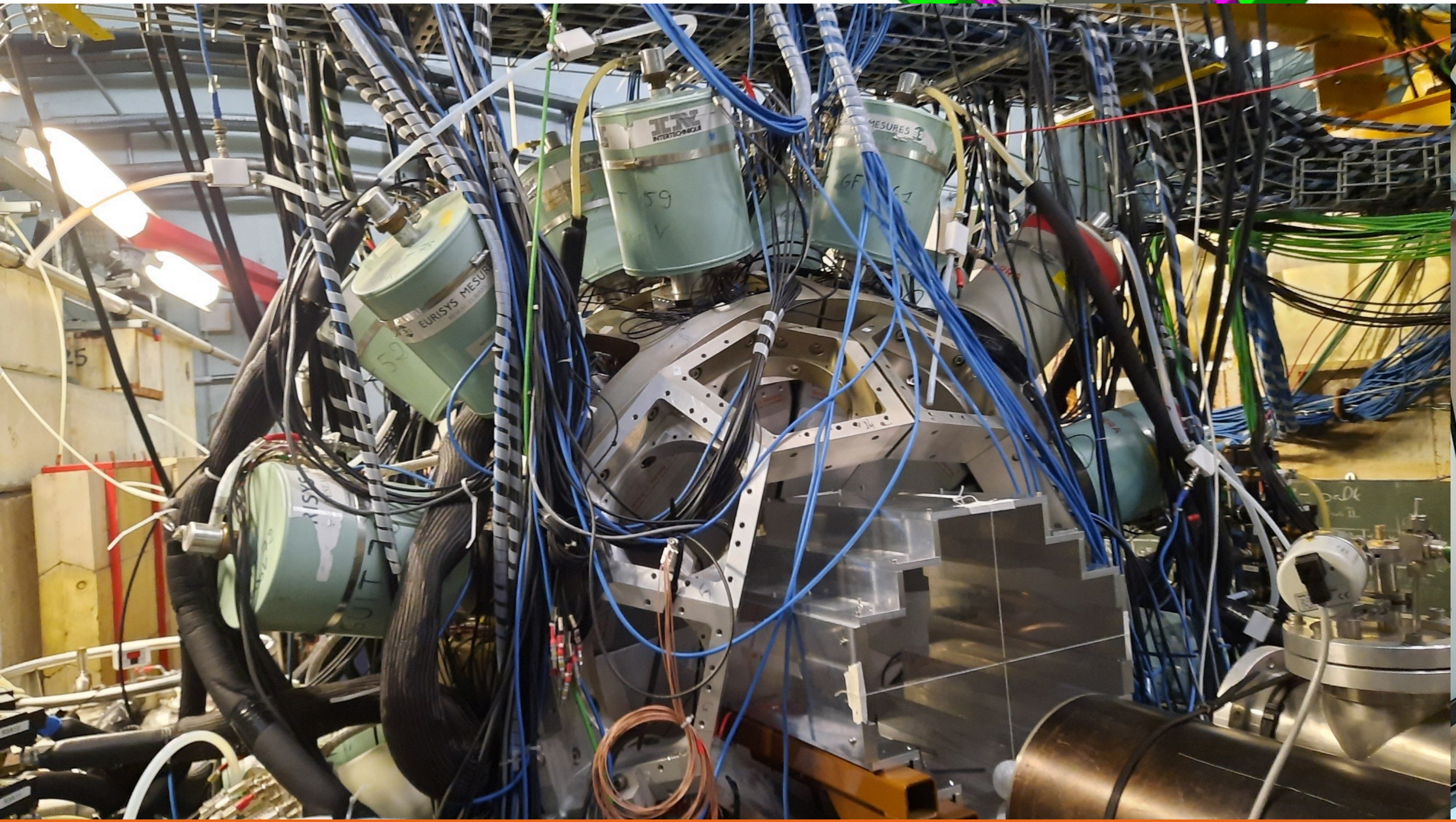
# nu-Ball2 successful coupling with PARIS + Warsaw DSSD

Thanks to A. Maj, I. Matea
P. Napiorkowski,
K. Hadynska-Klek





Record number of FASTER digital electronics channels (> 300). Triggerless.
5 synchronised crates



# nu-Ball2 completed experiments

ARIEL

| | | | |
|---|---|---|---|
| N-SI-126 | 28 CORTES-Martha Liliana_ | Shape evolution in N = Z nuclei: Lifetime measurements in 60Zn | Ge only |
| N-SI-121 | 21 MIERNIK-Krzysztof_ | Heavy-ion induced fusion-fission studies | Ge only |
| N-SI-120 | 63 RUDIGIER-Matthias_ | Spectroscopy of neutron-rich fission fragments produced in the 238U(n,f) reaction | FATIMA |
| N-SI-122 | 24 CIEMALA-Michal_ | Links between 80Sr compound nucleus' shape and its residue's deformation | PARIS |
| N-SI-129 | 42 WILSON-Jonathan_ | Detailed spectroscopy of fission isomers in uranium isotopes | PARIS/DSSD |
| N-SI-125 | 0 LEBOIS_Matthieu_ | nu-Ball2/FROZEN Proposal - Physics interests: Neutron-gamma de-excitation | PARIS/IC |
| N-SI-131 | 12 PASQUALATO-Giorgia_ | Evidence for enhanced collectivity in 58Fe examined through Coulomb excitation | PARIS/DSSD |
| N-SI-128 | 33 MATEJSKA-MINDA-Magda | Investigation of high spin structures in 44Ti and 42Ca via discrete and | PARIS/DSSD |
| N-SI-85 | 21 NAPIOROWSKI_Pawel | Coulomb excitation of super-deformed band in 40Ca | |
| N-SI-134 | 12 MIERNIK Krzysztof_ | Evidence for enhanced collectivity in 58Fe examined through Coulomb excitation | PARIS/DSSD |
| N-SI-136 | 30 HIVER Corentin | Search for the fission shape isomer in 232Th | PARIS/DSSD |
| N-SI-137 | 21 HADYNSKA-KLEK Kasia | Coulomb excitation of 62Ni | PARIS/DSSD |

in2p3/ COPIN

16 experiments approved, 12 ran, 300 Tb data collected, 160 international visitors
8 experiments financed by COPIN, EUROLABS and ARIEL

EURO-LABS

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- *Detailed spectroscopy of fission isomers in uranium isotopes*
  spokesperson J. Wilson
  data analysis C. Hiver

- *Evidence for enhanced collectivity in $^{58}$Fe examined through Coulomb excitation*
  spokespersons: G. Pasqualato, J. Ljungvall, A. Stuchbery
  data analysis G. Pasqualato

- *Coulomb excitation of super-deformed band in $^{40}$Ca*
  spokespersons: P. Napiorkowski, A. Maj, F. Azaiez
  data analysis: K. Hadyńska-Klęk, J. Samorajczyk-Pyśk

- *$^{194,196}$Hg fission studies*
  spokesperson and data analysis: K. Miernik

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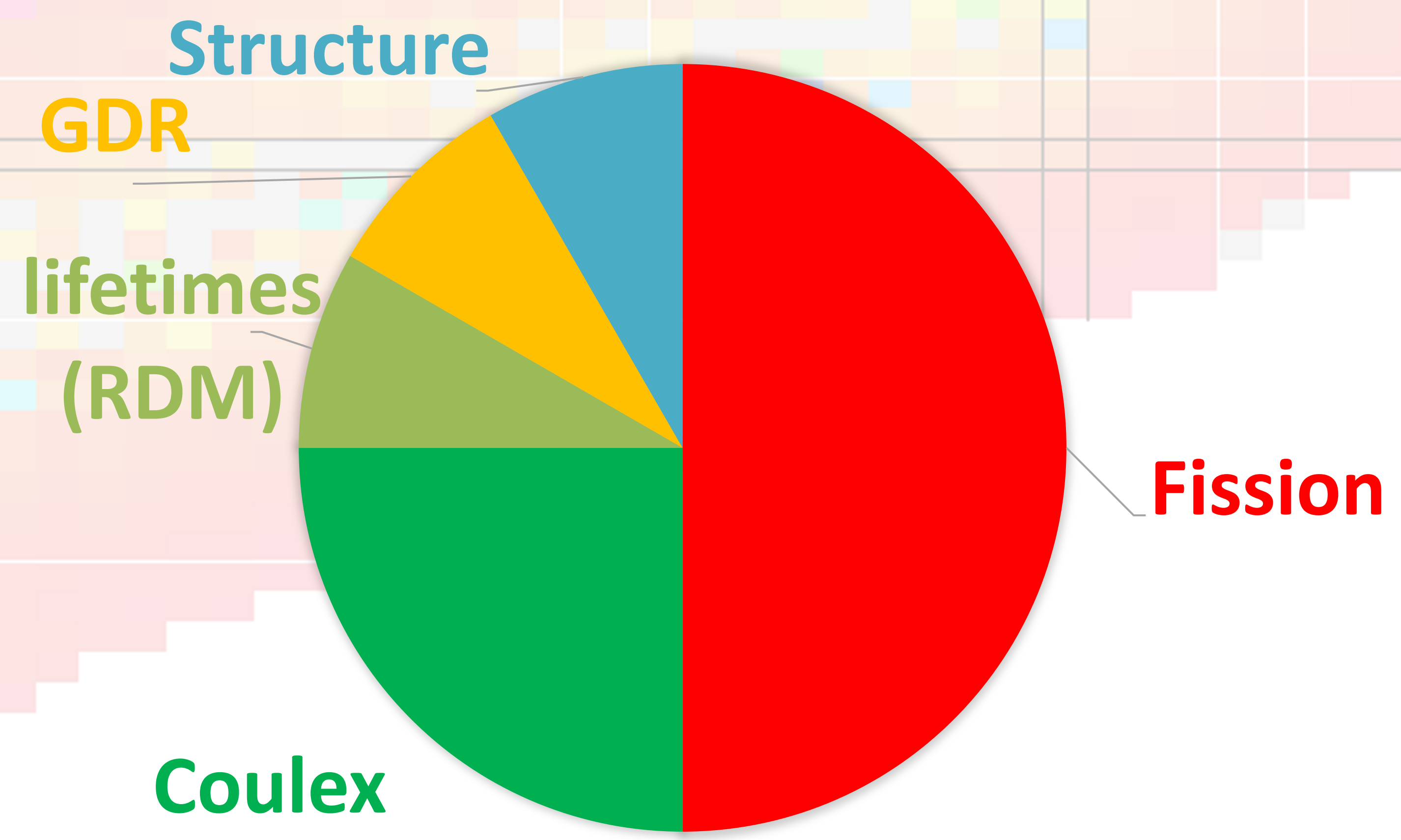

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*(see next talk - J. Wilson)*

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K. Hadyńska-Klęk

J. Wilson

# Experimental campaign: IJC Lab, Orsay

**nuBALL2:**

2 rings of 12+12 HPGe CLOVERS + ACS

Eff. ~4%

**SiLCA DSSD:**

32 sectors + 16 rings

125-152$^{o}$

**PARIS:**

LaBr3 / CeBr3 + NaI array

15 cm from the target

Eff. ~14%

**FASTER**

fully digital readout of all channels


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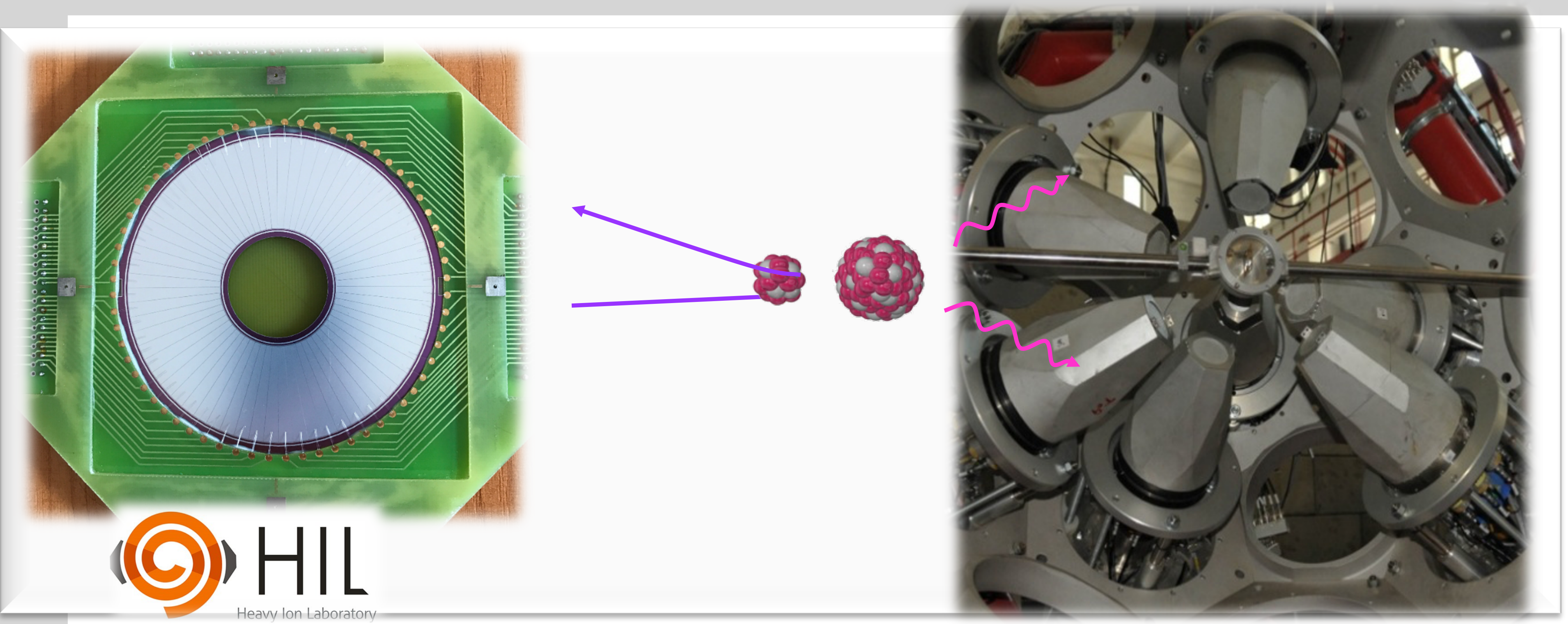
# SilCA - Silicon Coulex Array



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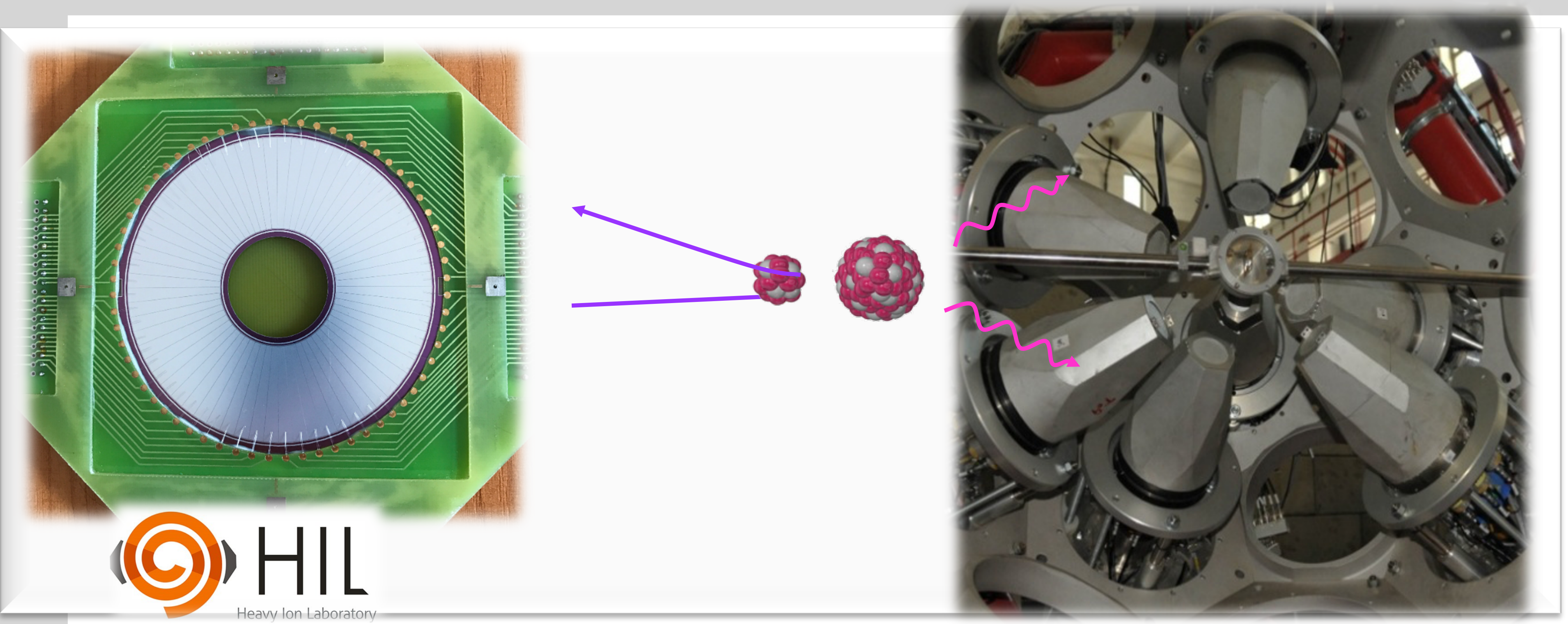


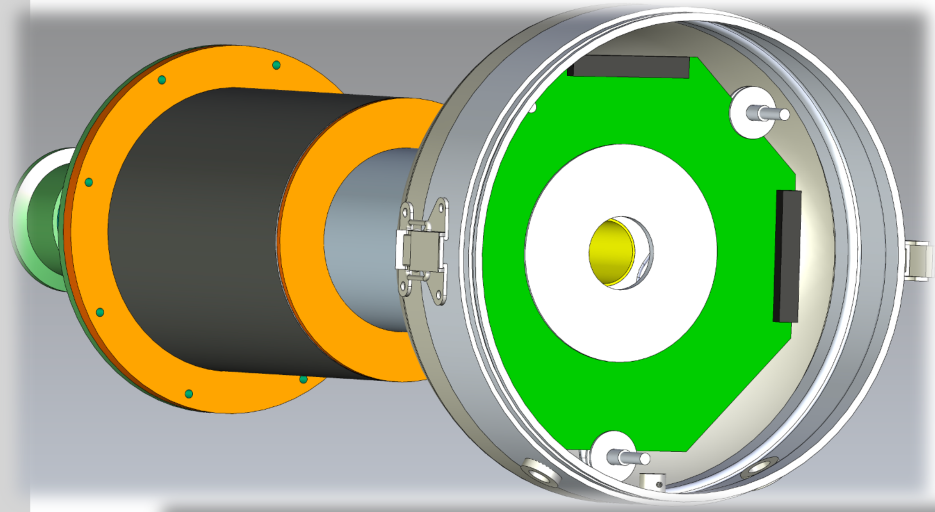

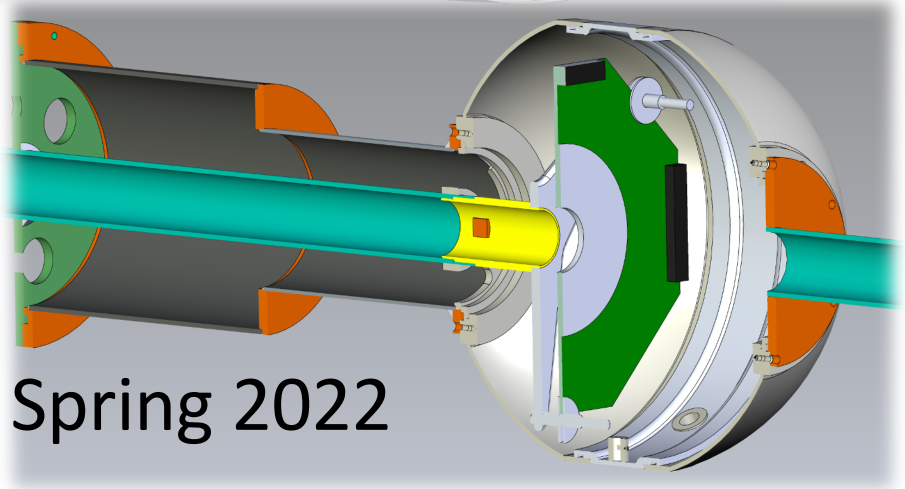


- $r_{in}$ = 1.6 cm
- $r_{out}$ = 4.2 cm
- 64 sectors (32 readout)
- 32 rings (16 readout)
- Digital electronics

*Project: P. Napiorkowski, J. Iwanicki, A. Iwanicki, J. Mierzejewski, KHK*

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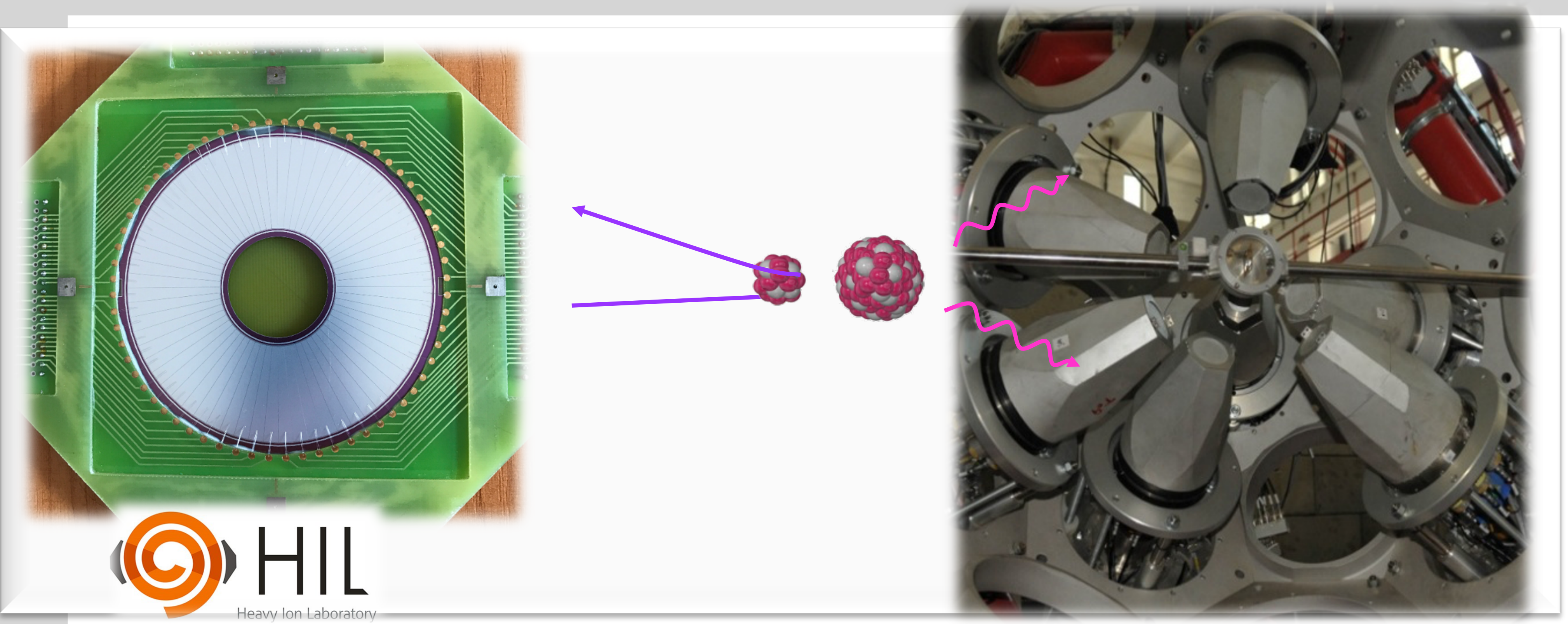

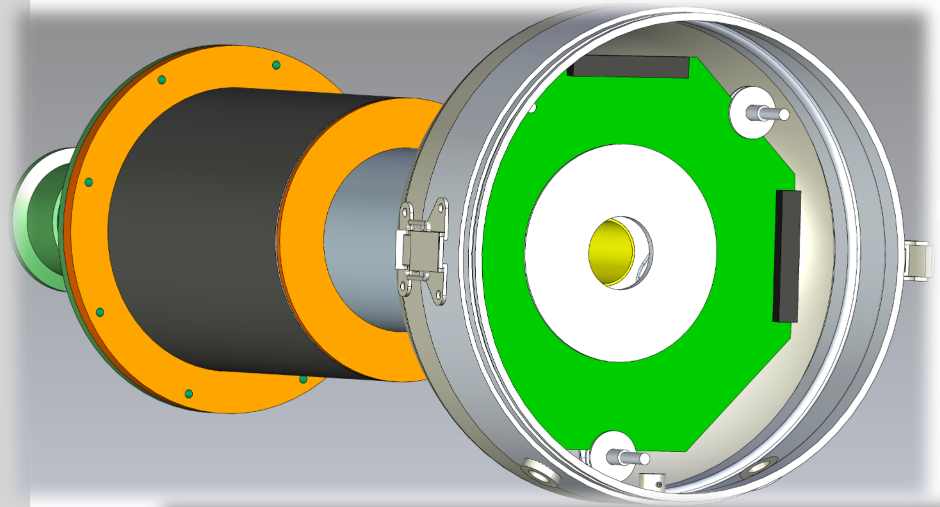

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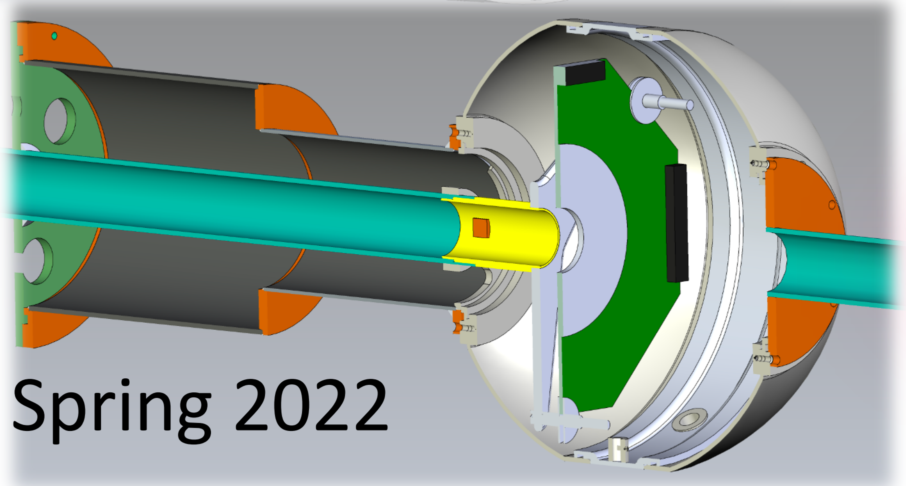


October 2022

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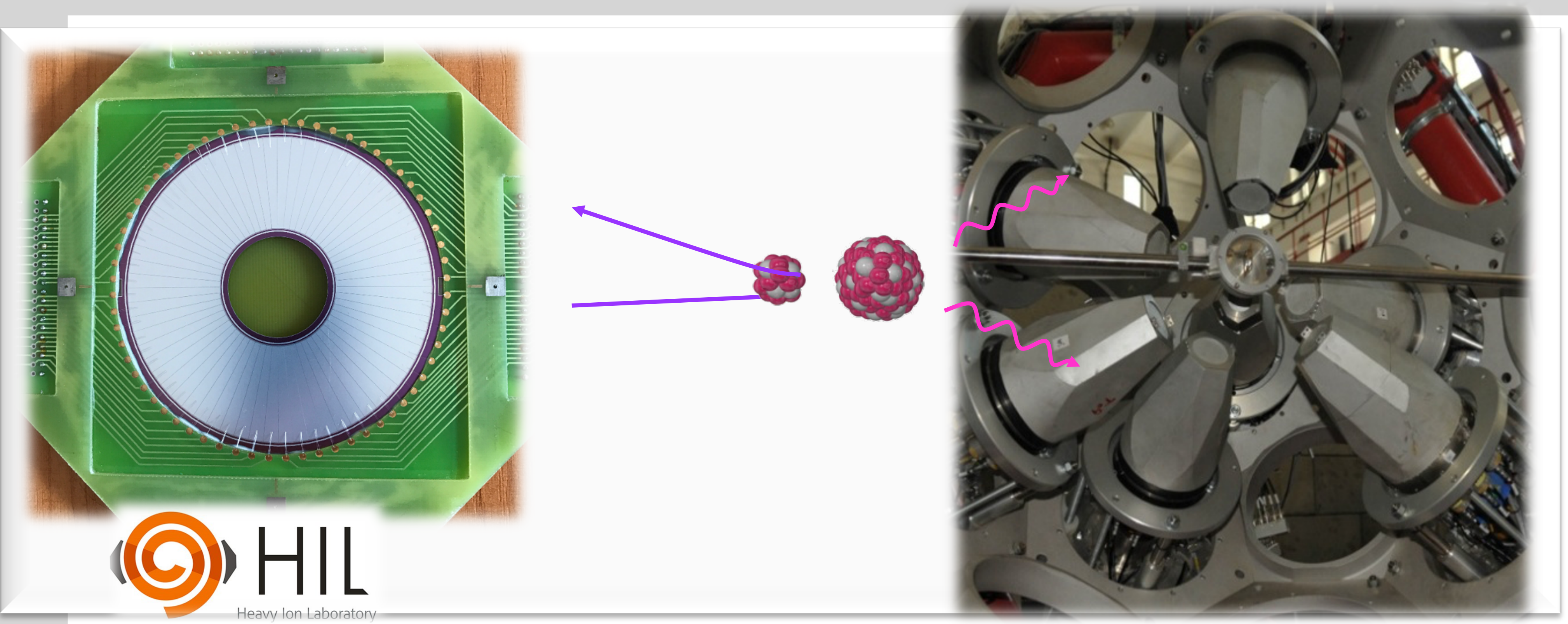


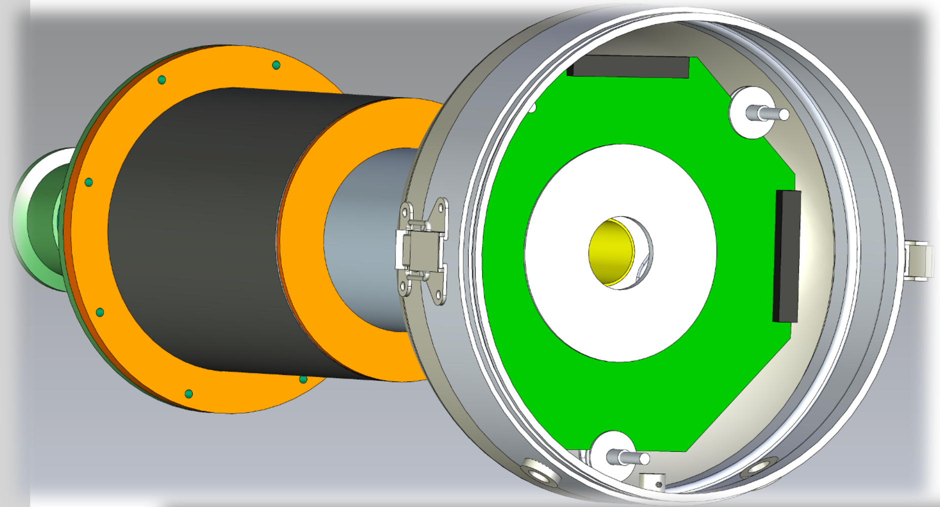

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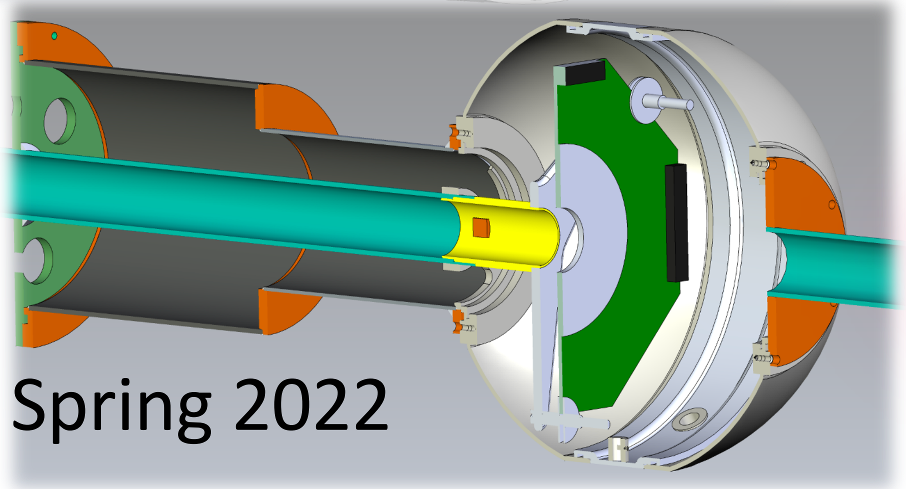


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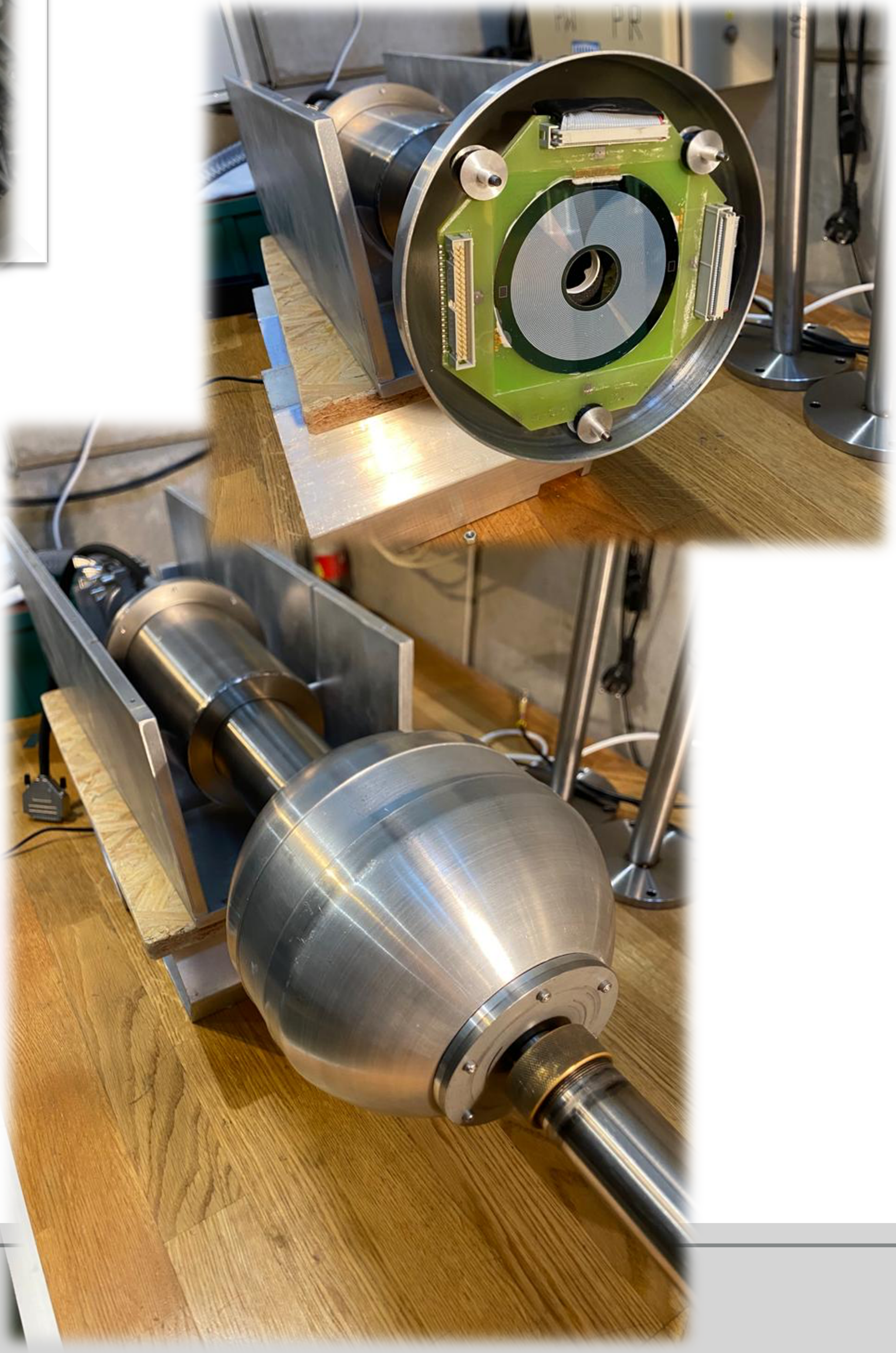

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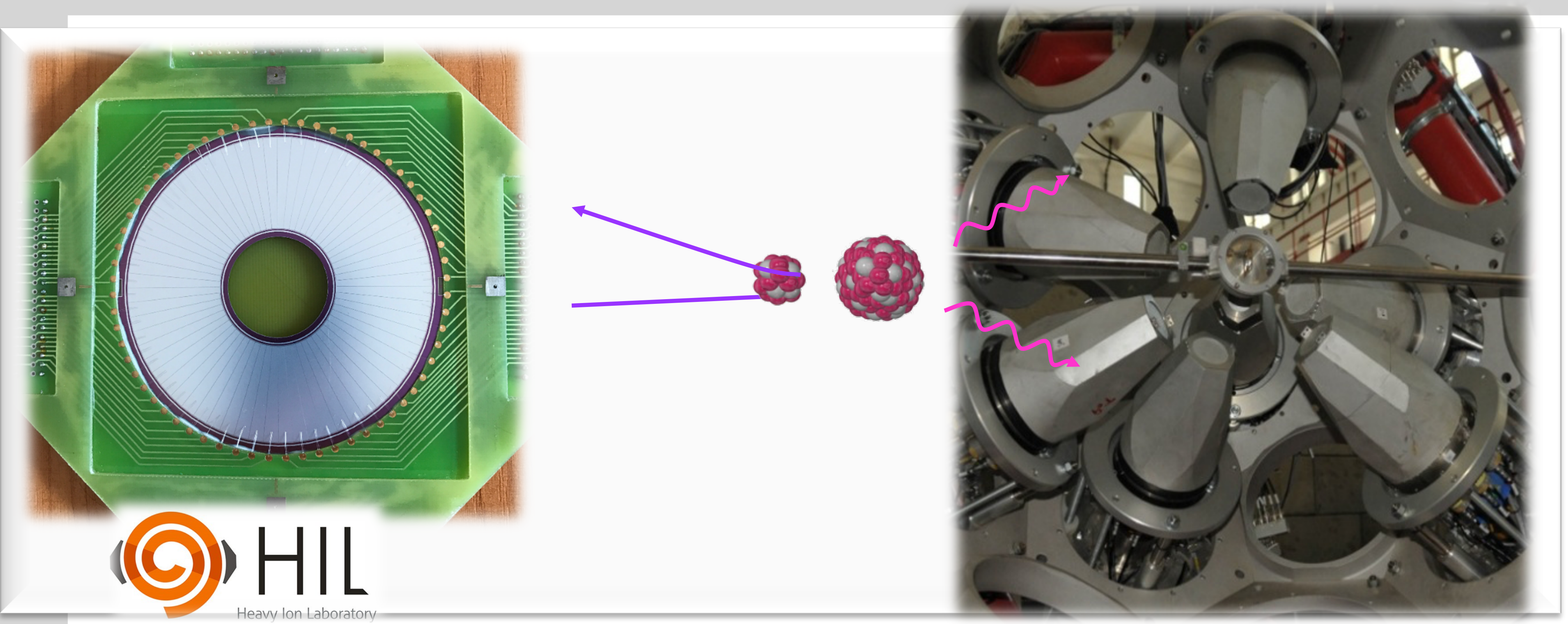


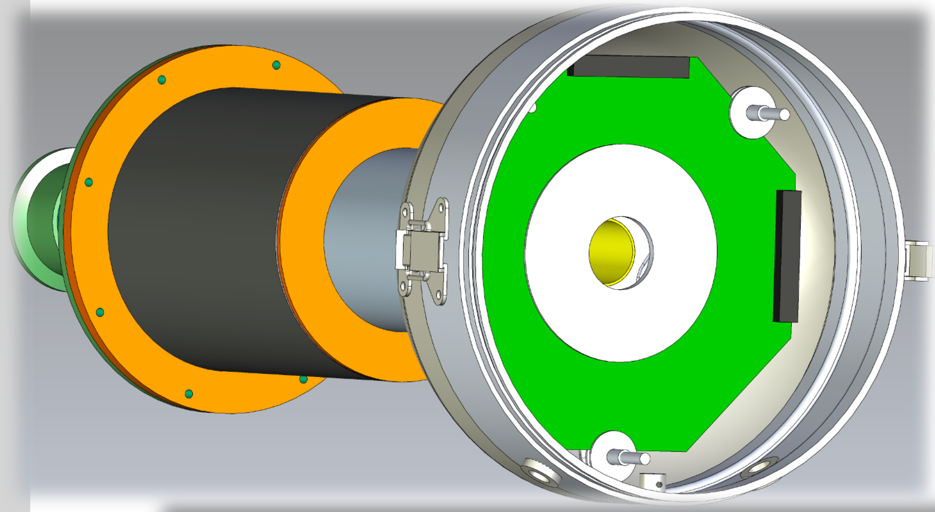

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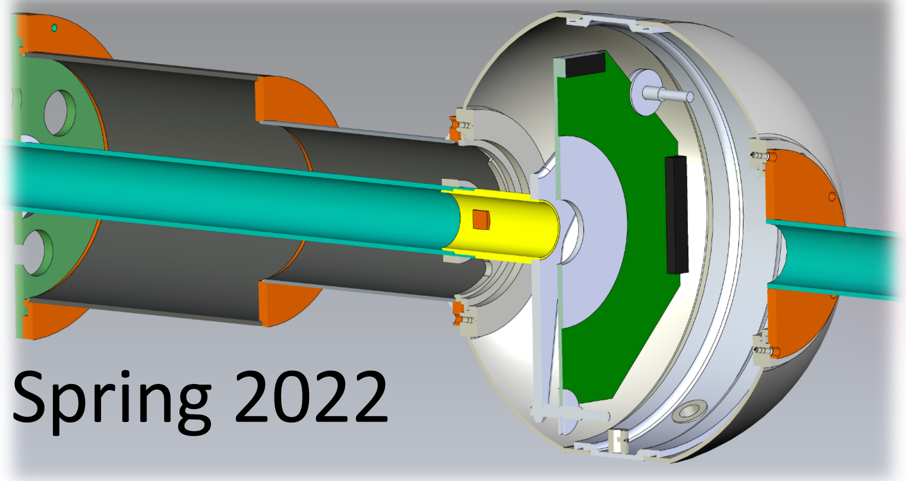

Spring 2022

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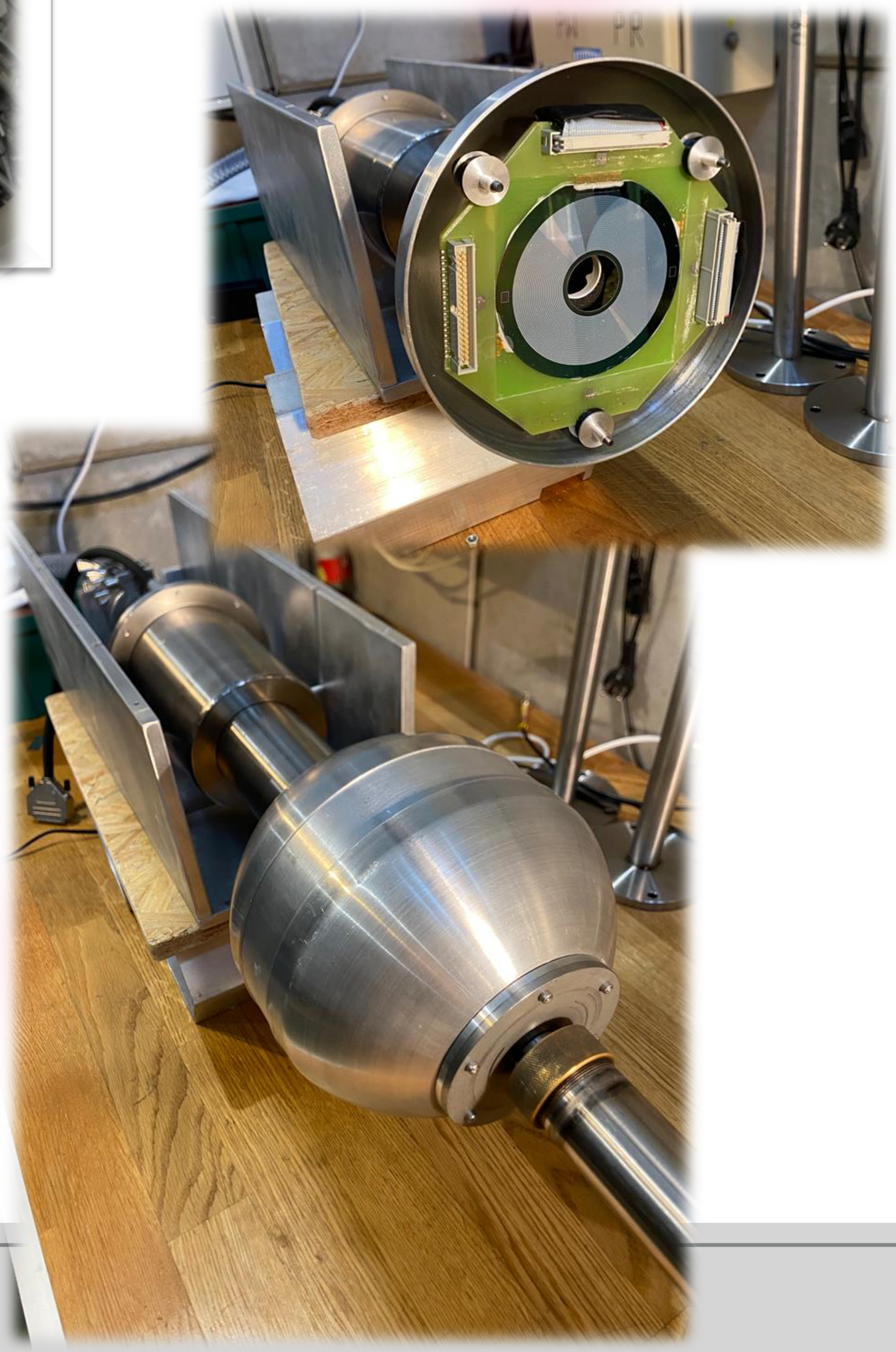

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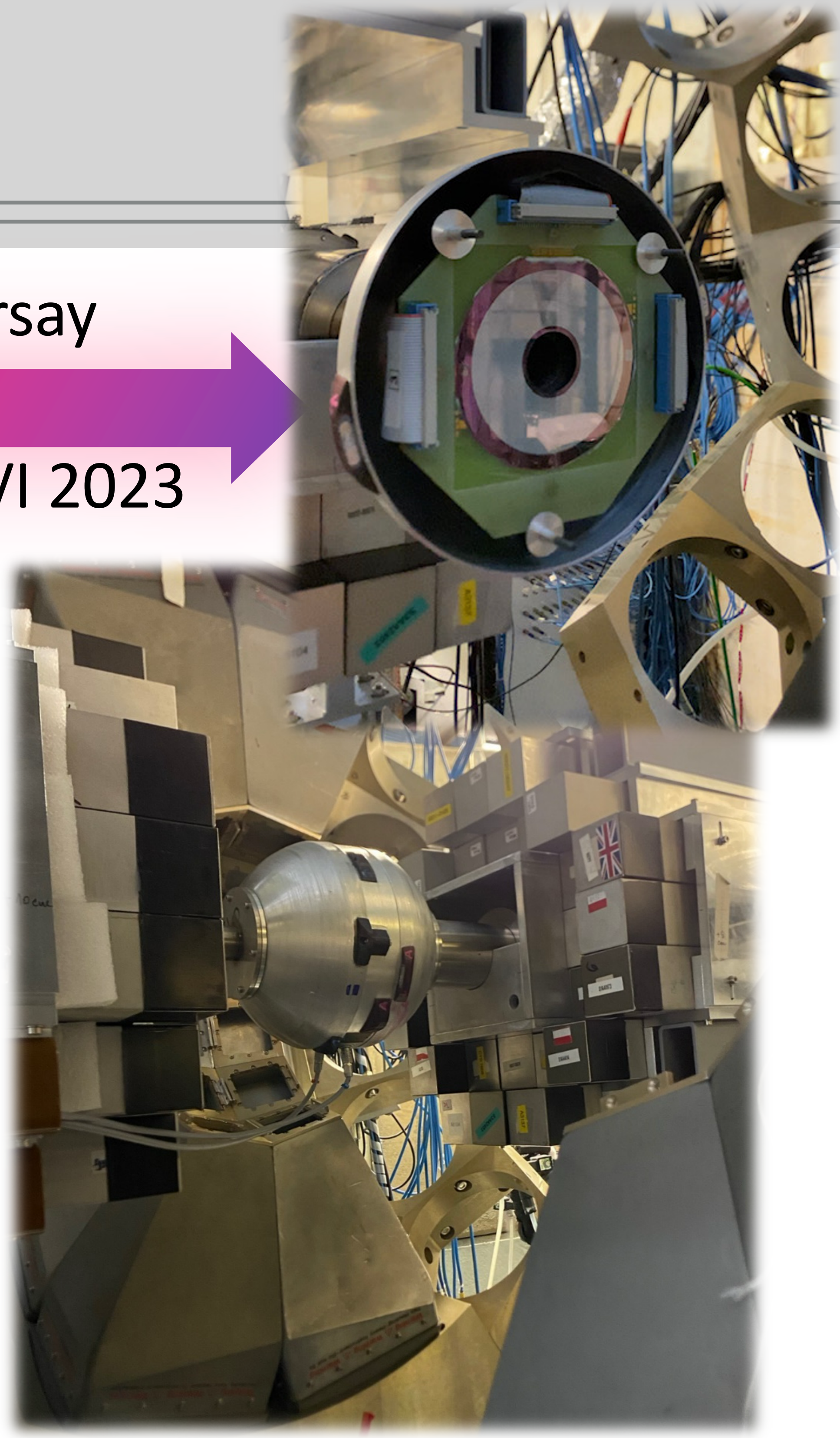
Campaign I-VI 2023



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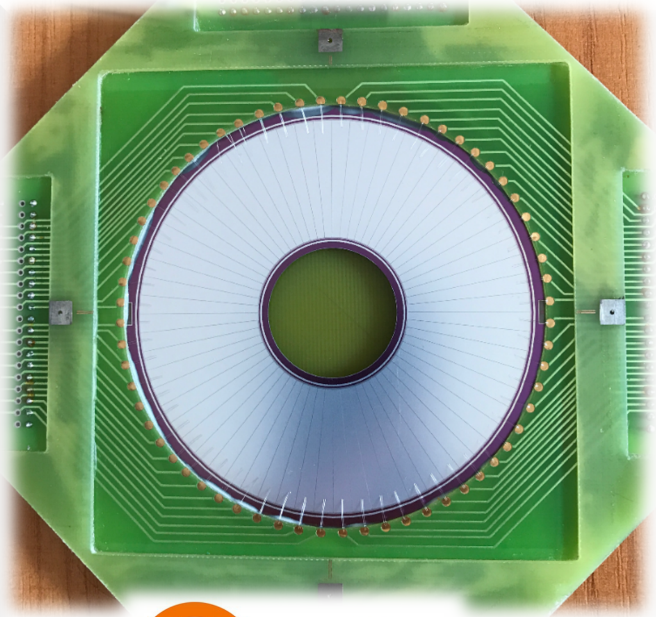

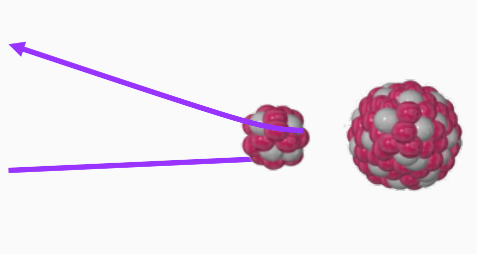

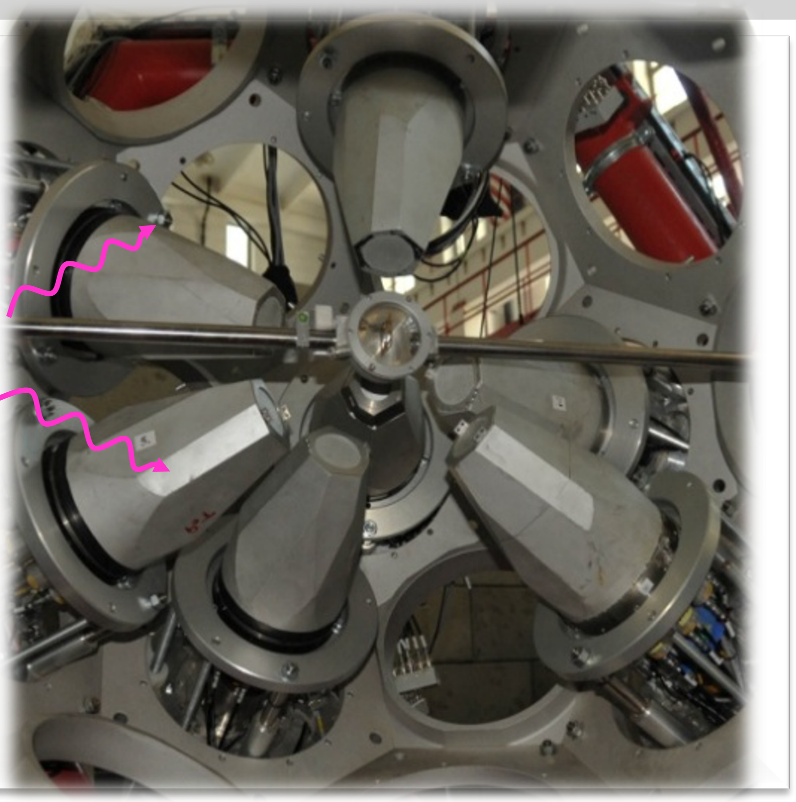

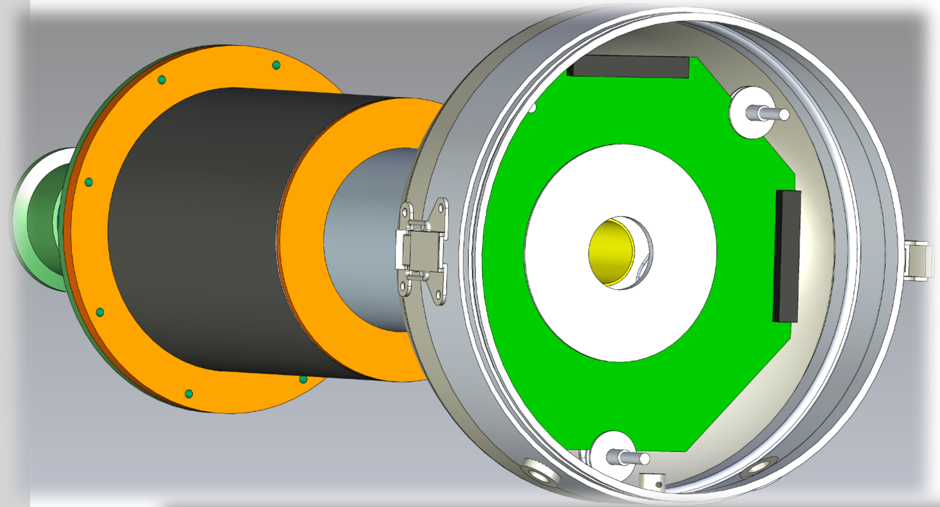

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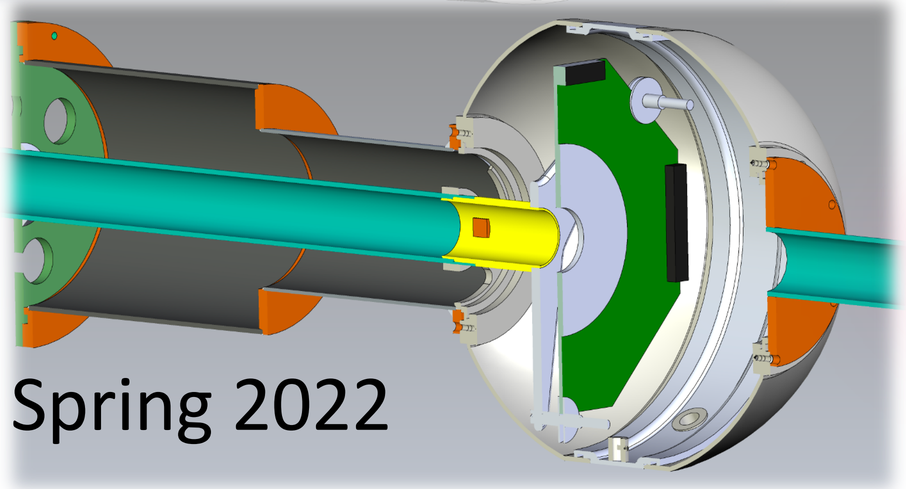


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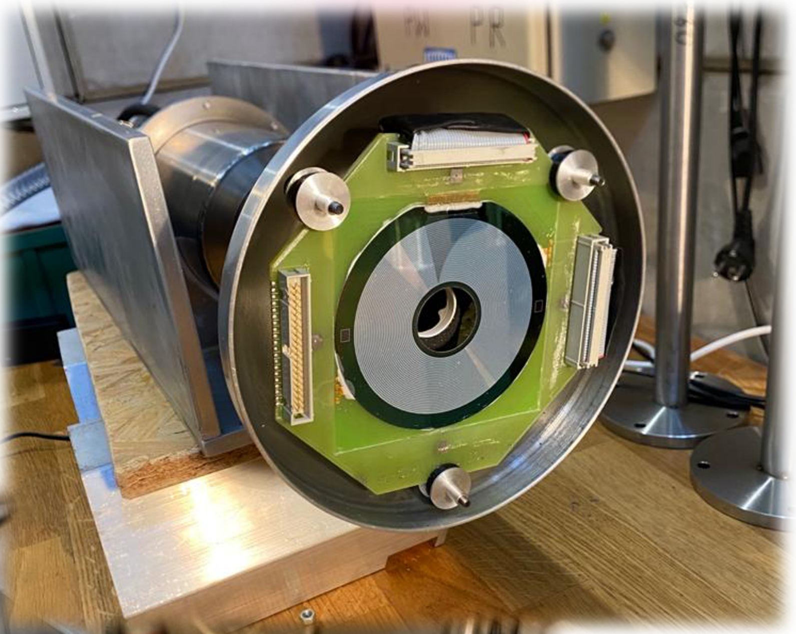

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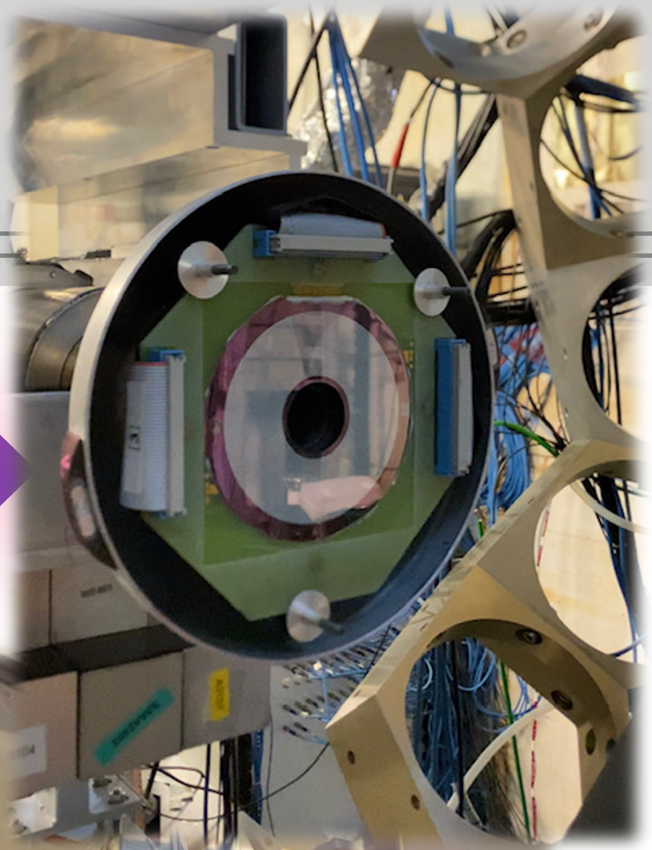

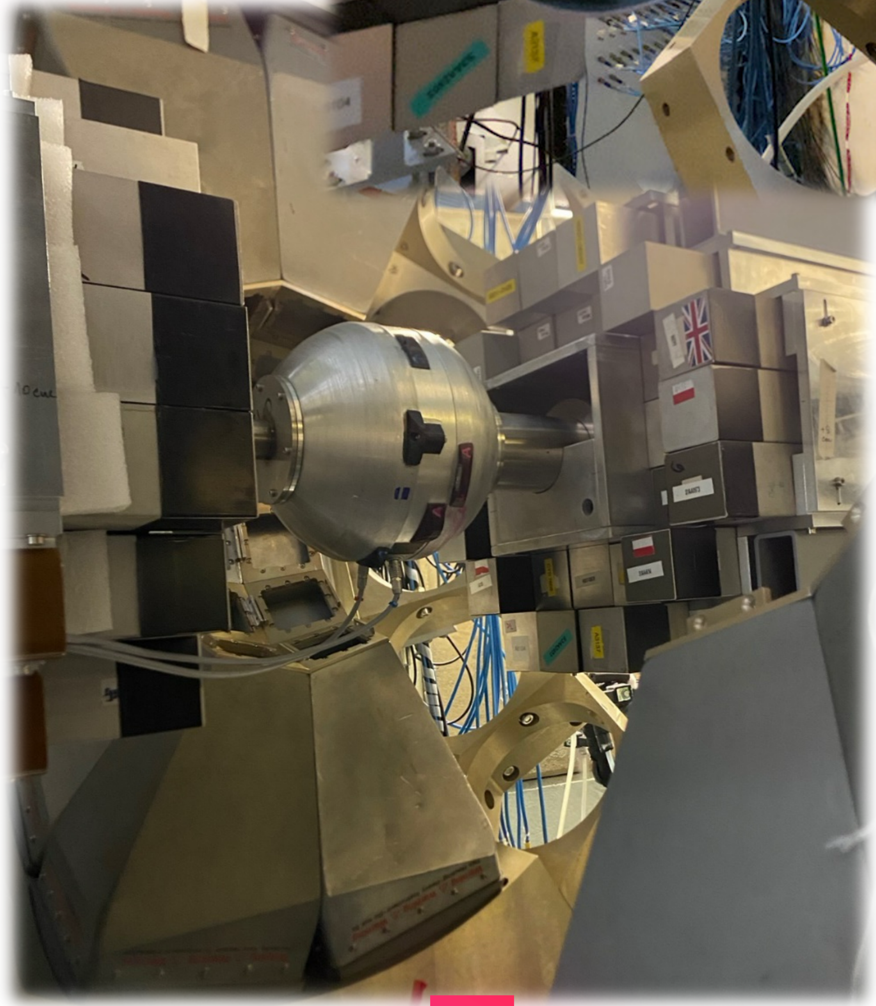

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  spokesperson J. Wilson
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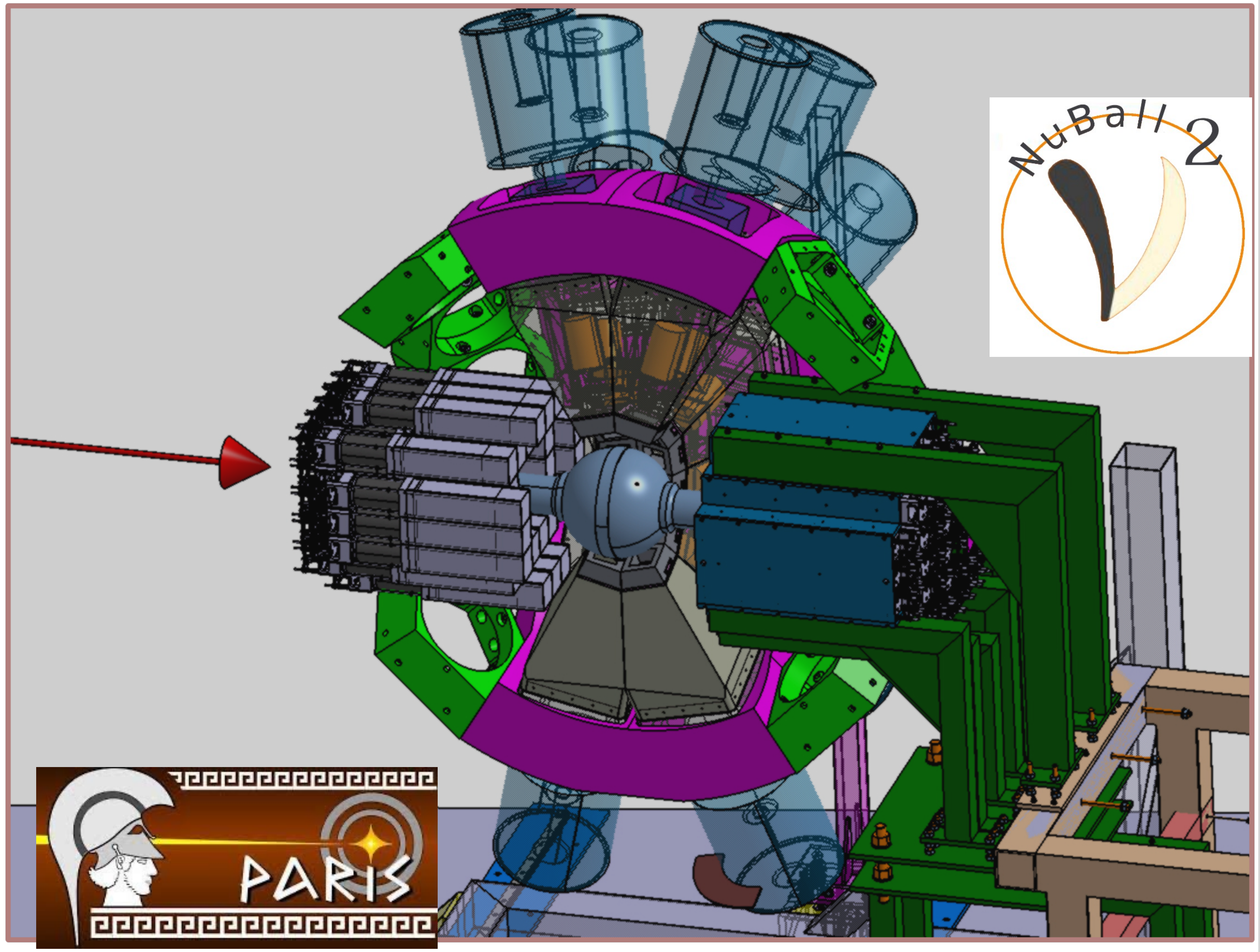


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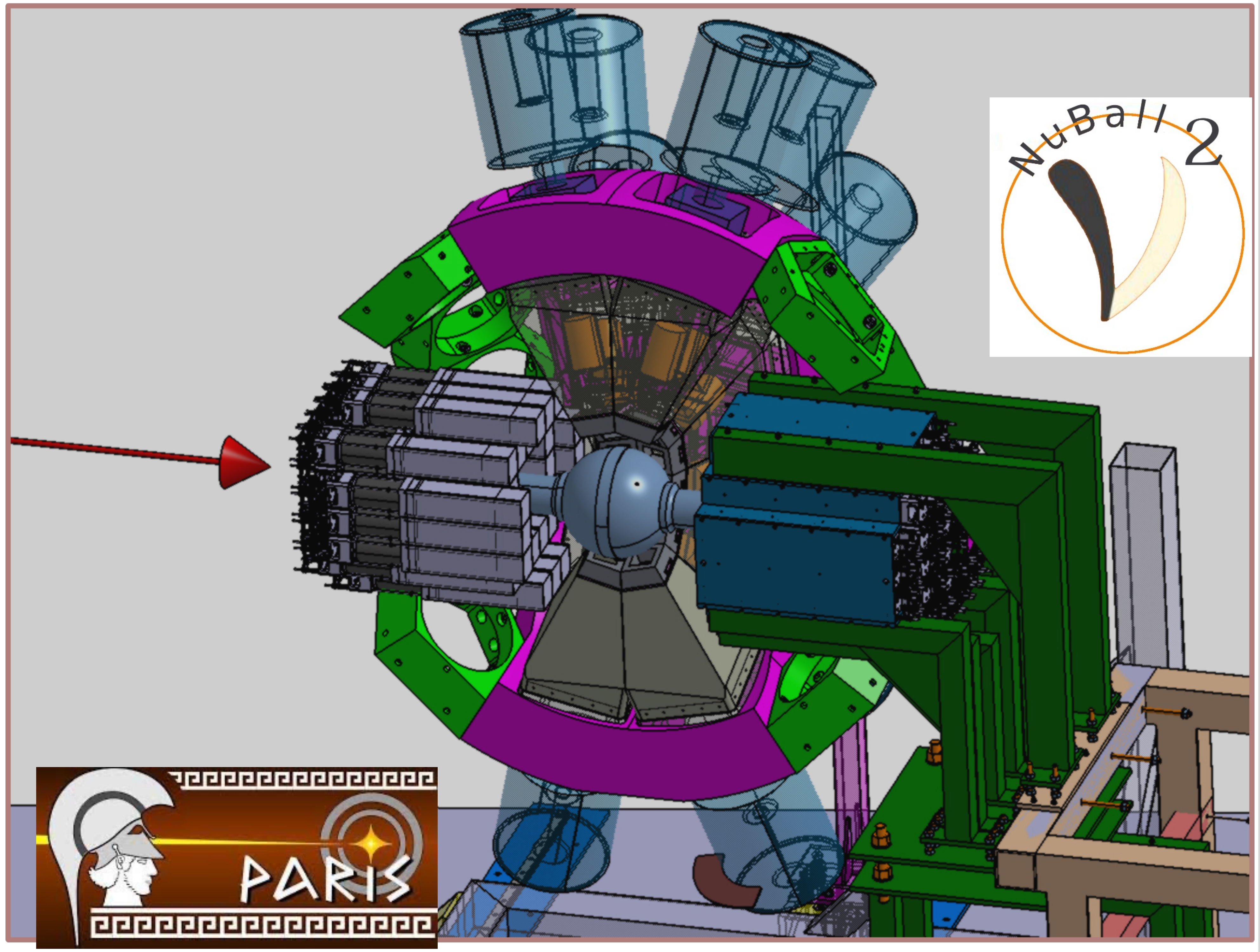
40Ca beam very unstable
2 days of the data taking
197Au target

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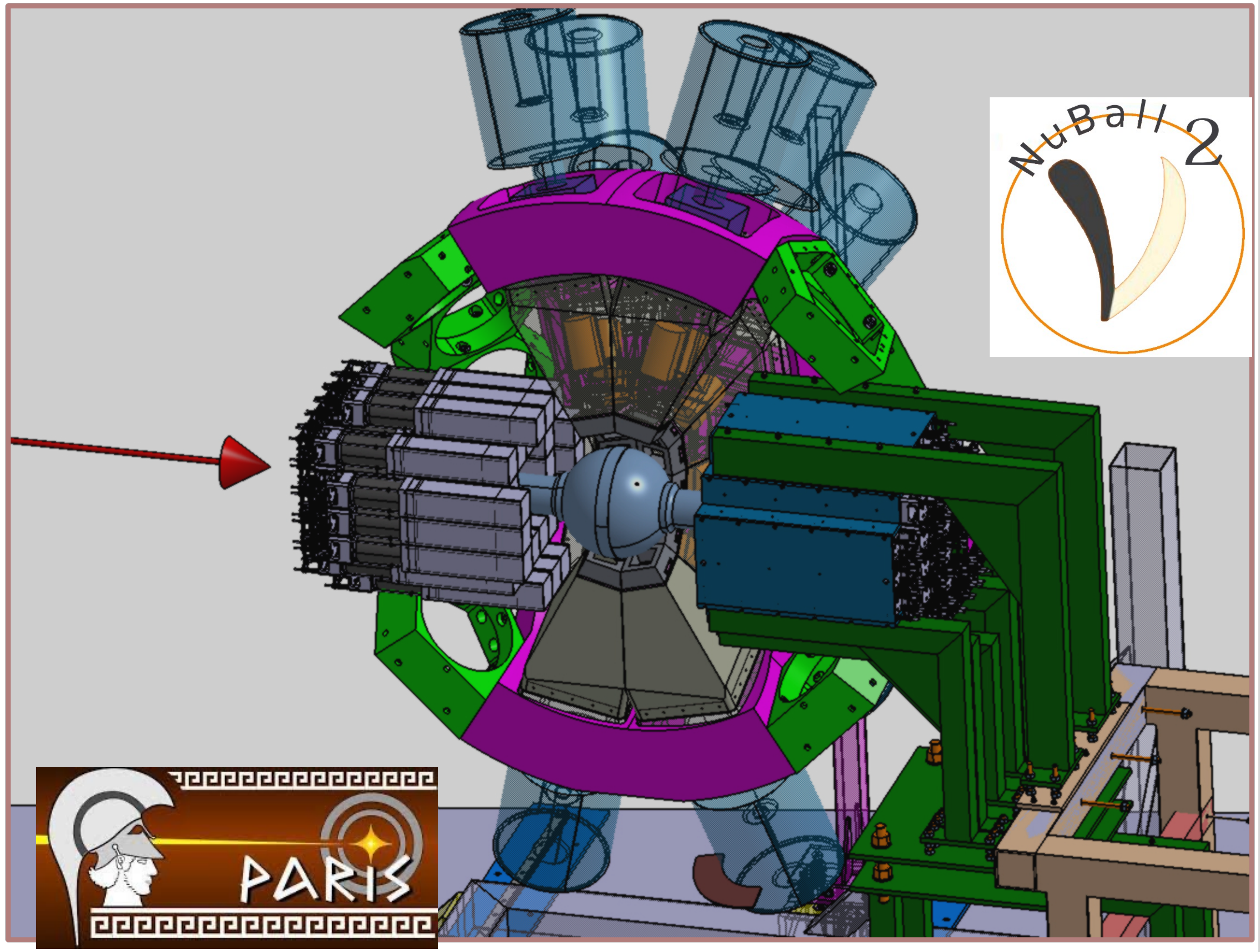


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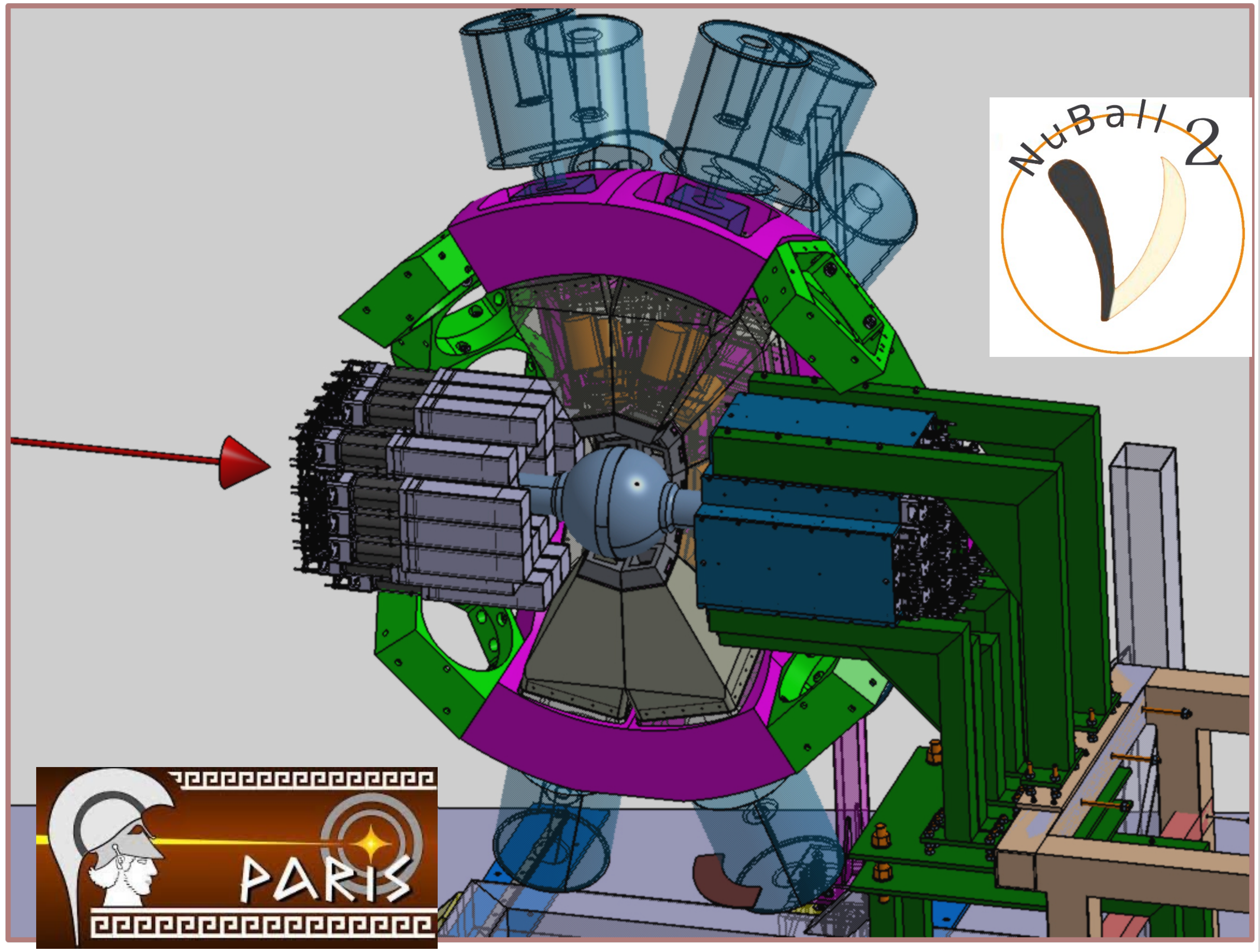
24Mg beam difficult,
3 days of data taking, ~24 enA

✓ ***Emergence of collectivity near magic nuclei: Coulomb-excitation of $^{62}$Ni*    (* $^{60}$Ni)***
spokespersons: : K. Hadyńska-Klęk, M. Rocchini, N. Marchini
data analysis: K. Hadyńska-Klęk

62Ni was not possible
beam changed to 60Ni
a new physics case, 197Au target
5 days of data taking, ~30 enA

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# Experimental campaign
(K. Hadyńska-Klęk)

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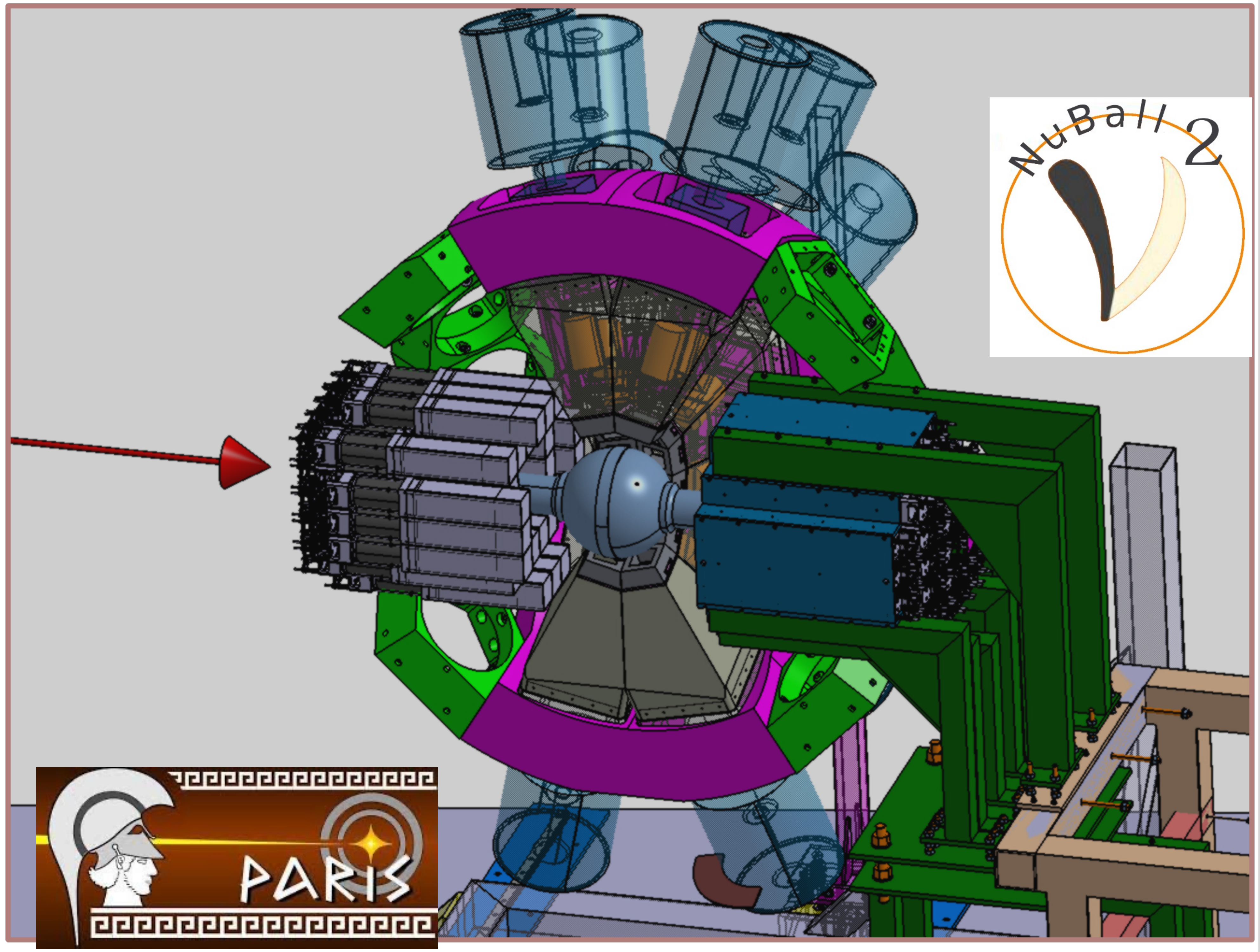

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# COULEX of $^{58}Fe$ (N-SI-128)

$^{58}Fe$ (Z=26) is placed in the border of a region in the nuclear chart where a development of collectivity has been observed and predicted*.

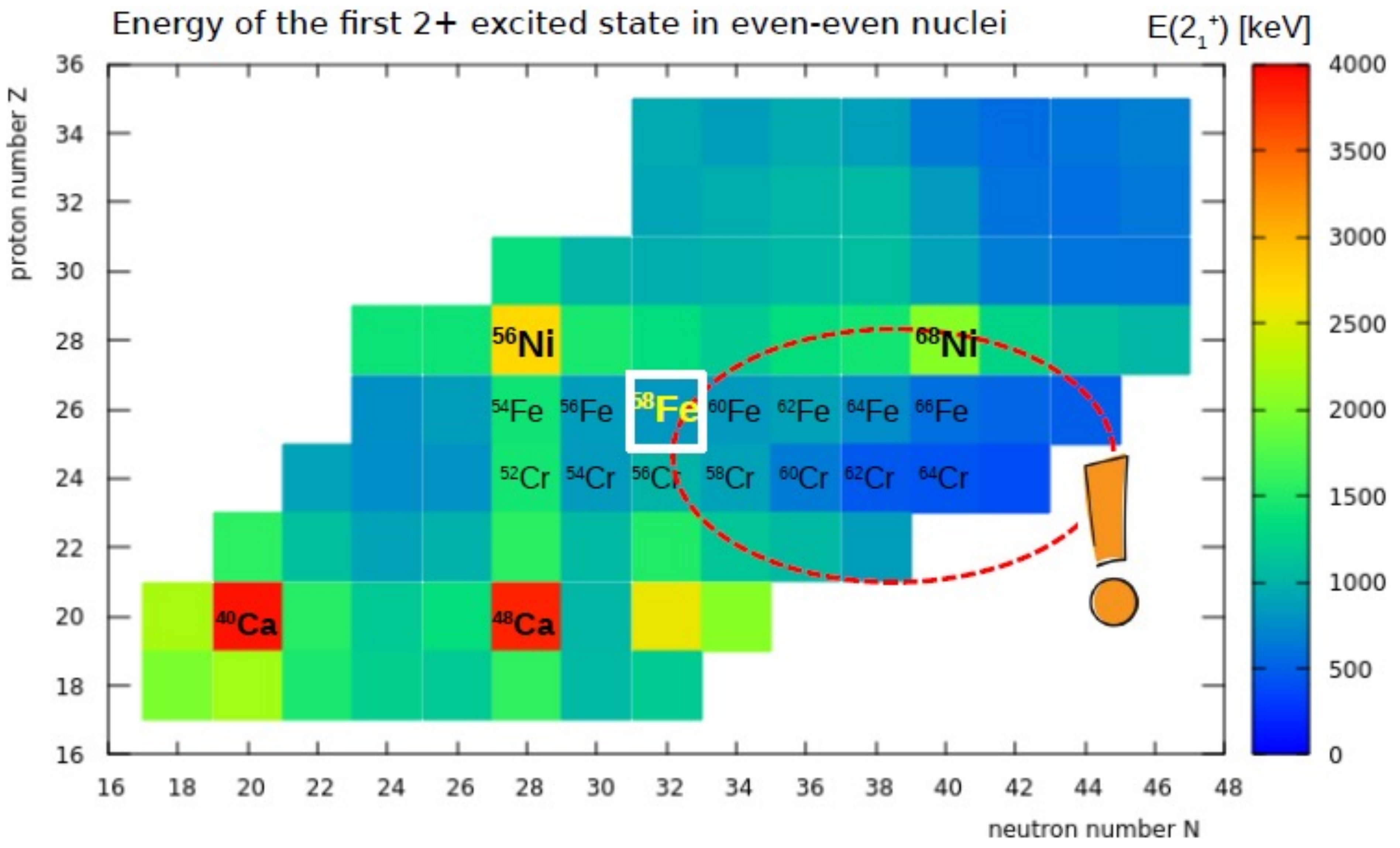
+

Proximity to the Z=28, N=40 doubly-magic nucleus $^{68}Ni$.

Contrast between two opposite behaviors:

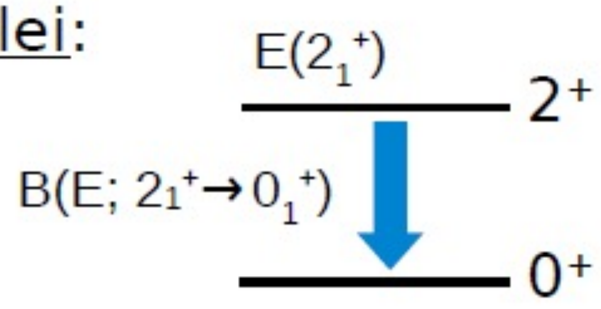
- Collectivity: nuclear states can be described as the collective motion (the interaction) between many valence nucleons.
  → **easy to excite**

- Single-particle: only few nucleons are involved on the definition of the nuclear states wave functions
  → **pretty stable over excitation**




Fingerprints of collectivity in nuclei:

- Small $E(2^+)$
- Large $B(E2)$




*Courtesy: Giorgia Pasqualato, IJC Lab, Orsay*

# COULEX of $^{58}Fe$ (N-SI-128)

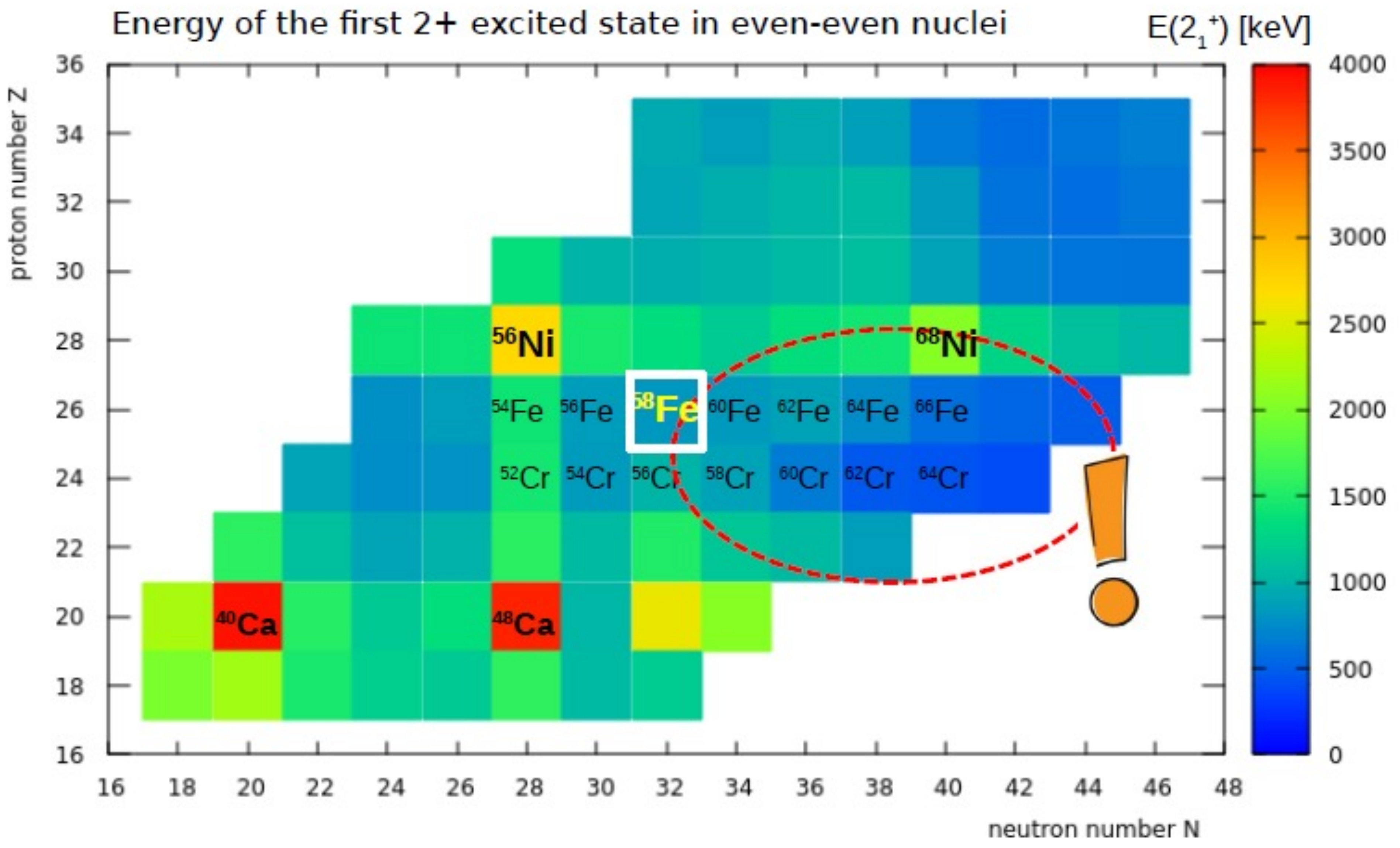
$^{58}Fe$ (Z=26) is placed in the border of a region in the nuclear chart where a development of collectivity has been observed and predicted*.

+

Proximity to the Z=28, N=40 doubly-magic nucleus $^{68}Ni$.

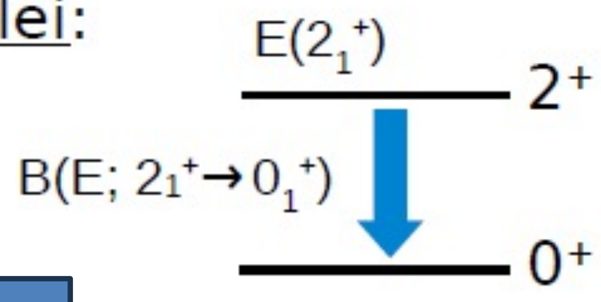
Contrast between two opposite behaviors:

- Collectivity: nuclear states can be described as the collective motion (the interaction) between many valence nucleons.
  → **easy to excite**
- Single-particle: only few nucleons are involved on the definition of the nuclear states wave functions
  → **pretty stable over excitation**




<u>Fingerprints of collectivity in nuclei</u>:

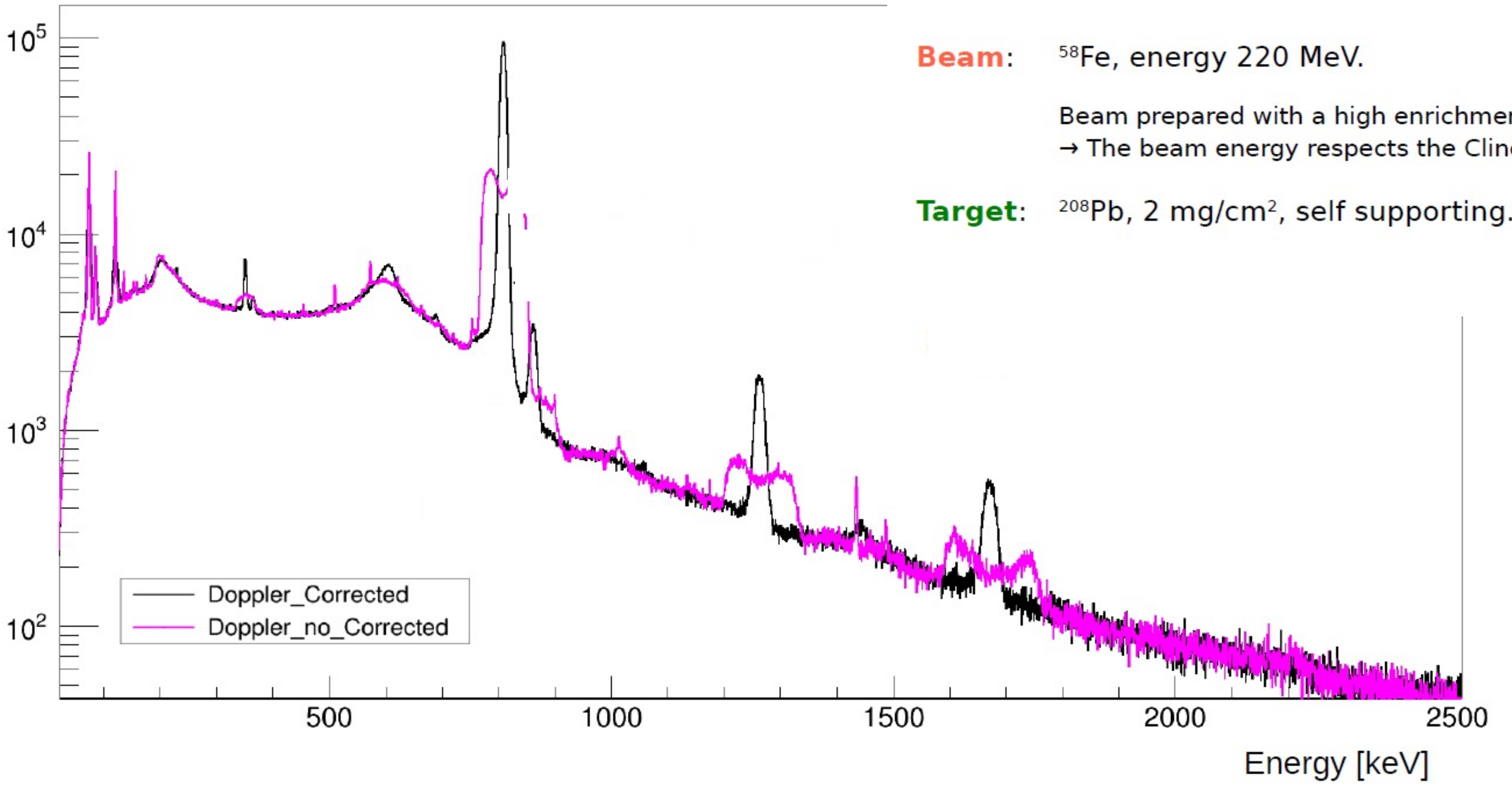
- Small E($2^+$)
- Large B(E2)




**N-SI-128**

*Courtesy: Giorgia Pasqualato, IJC Lab, Orsay*

# COULEX of $^{58}Fe$ – preliminary results



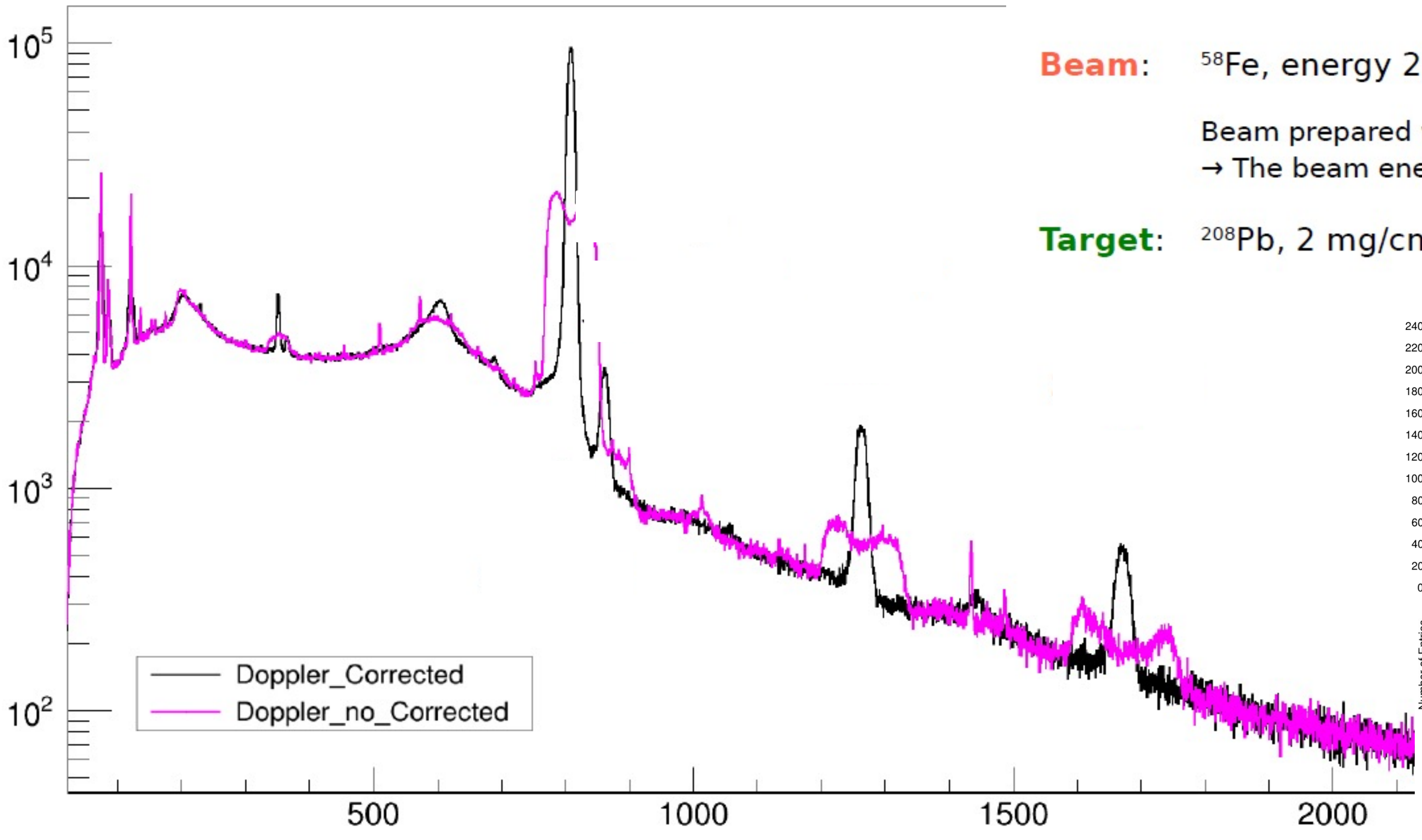

**Beam**: $^{58}Fe$, energy 220 MeV.

Beam prepared with a high enrichment of $^{58}Fe$.
→ The beam energy respects the Cline safe-energy criteria

**Target**: $^{208}Pb$, 2 mg/cm$^2$, self supporting.

*Courtesy: Giorgia Pasqualato, IJC Lab, Orsay*

# COULEX of $^{58}Fe$ – preliminary results




**Beam**: $^{58}Fe$, energy 220 MeV.

Beam prepared with a high enrichment of $^{58}Fe$.
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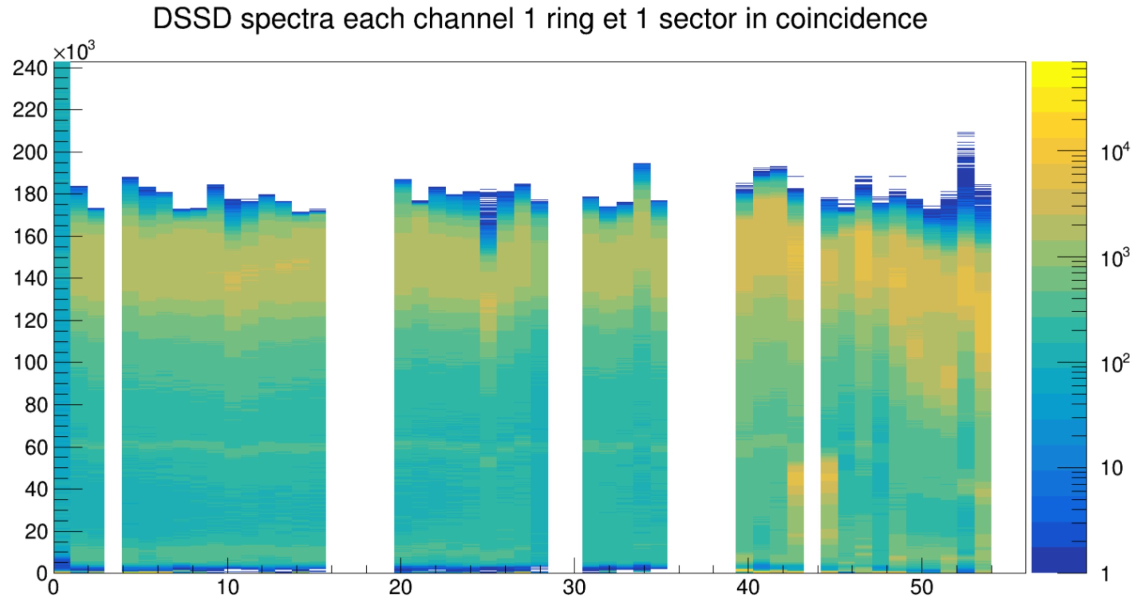
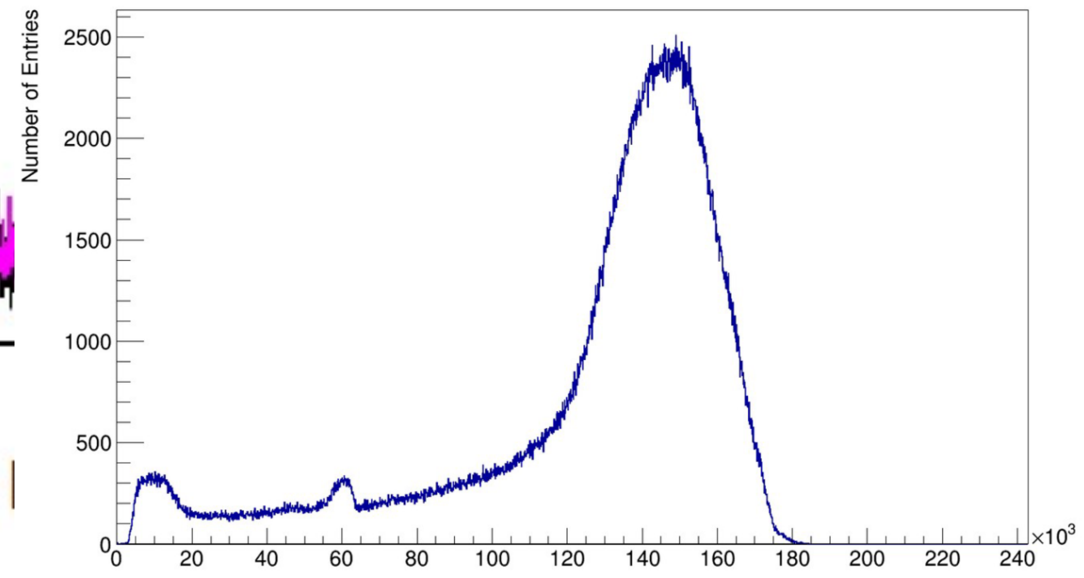
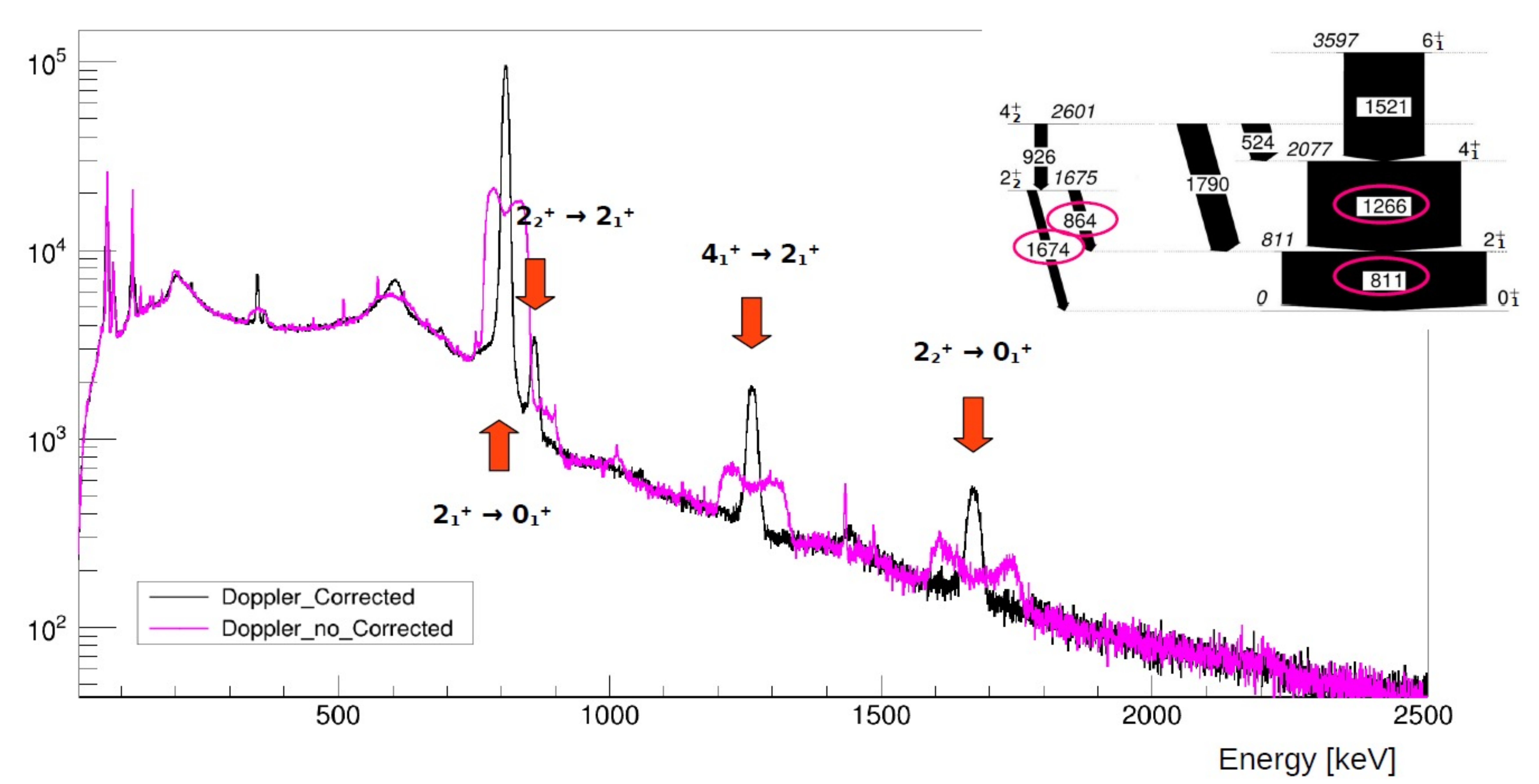


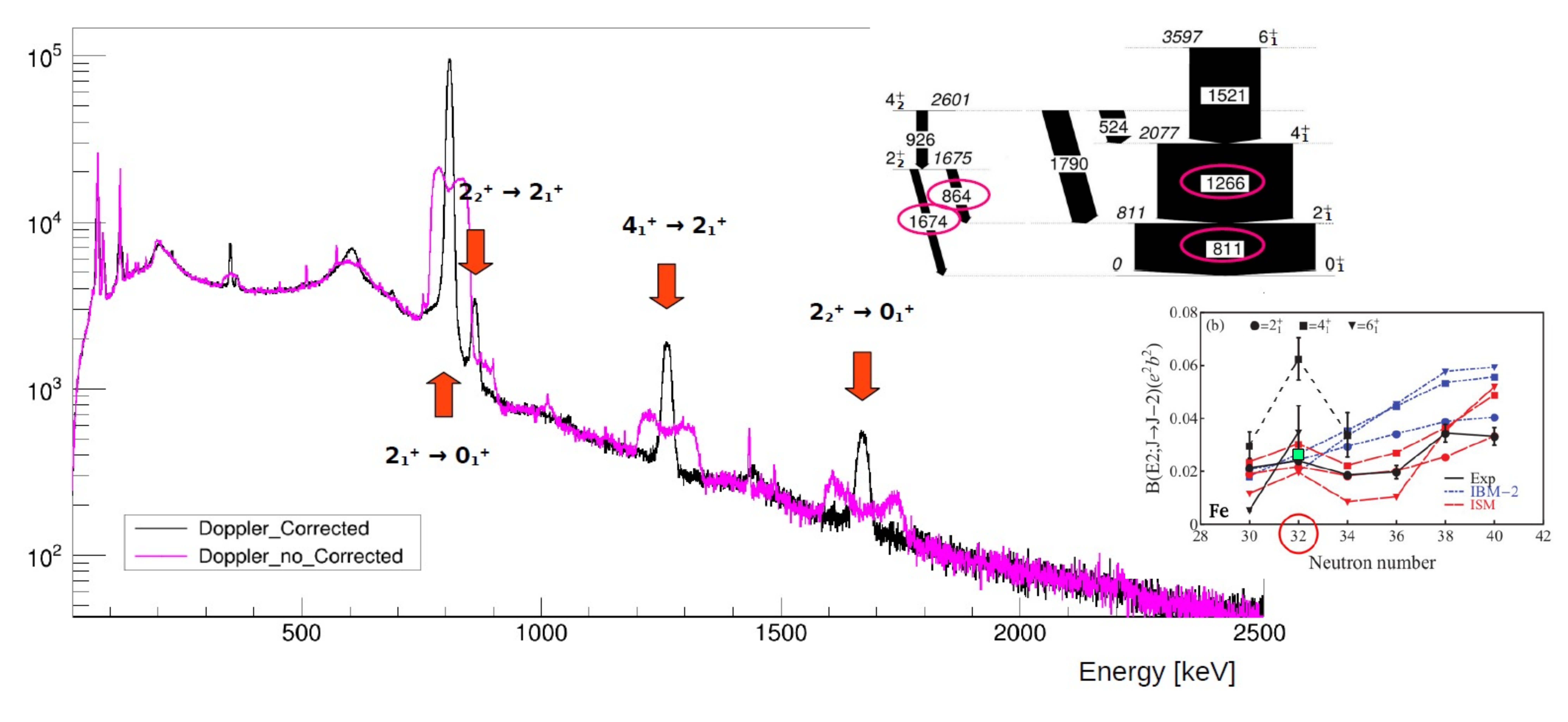

*Courtesy: Giorgia Pasqualato, IJC Lab, Orsay*

# COULEX of $^{58}Fe$ - preliminary results




Courtesy: *Giorgia Pasqualato, IJC Lab, Orsay*

# COULEX of $^{58}Fe$ – preliminary results




Courtesy: *Giorgia Pasqualato, IJC Lab, Orsay*

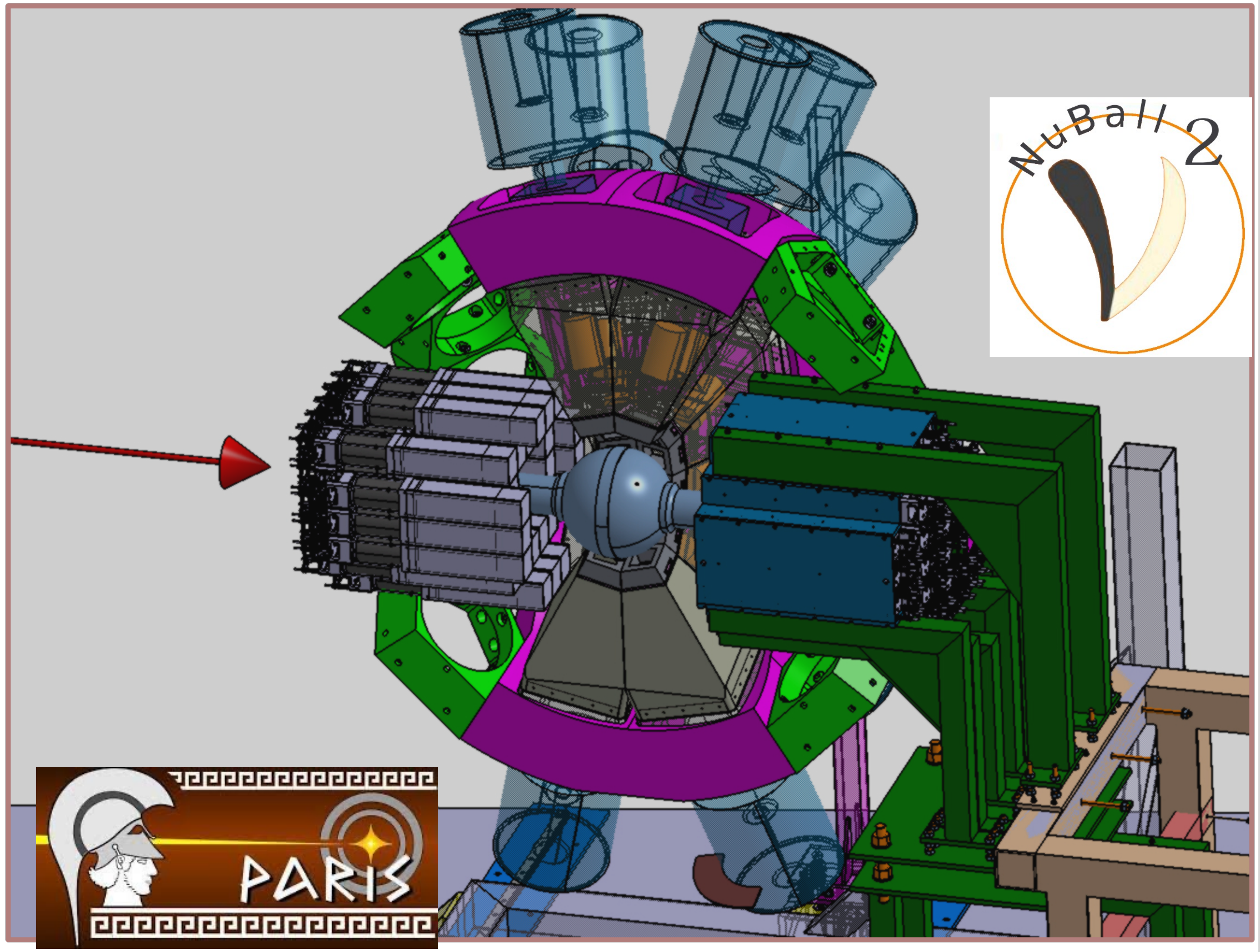
# Experimental campaign: IJC Lab, Orsay

**Winter 2022-2023**

- ✓ ***Detailed spectroscopy of fission isomers in uranium isotopes***
  spokesperson J. Wilson
  data analysis C. Hiver

- ✓ ***Evidence for enhanced collectivity in $^{58}$Fe examined through Coulomb excitation***
  spokespersons: G. Pasqualato, J. Ljungvall, A. Stuchbery
  data analysis G. Pasqualato

- ❑ ***Coulomb excitation of super-deformed band in $^{40}$Ca***
  spokespersons: P. Napiorkowski, A. Maj, F. Azaiez
  data analysis: K. Hadyńska-Klęk, J. Samorajczyk-Pyśk

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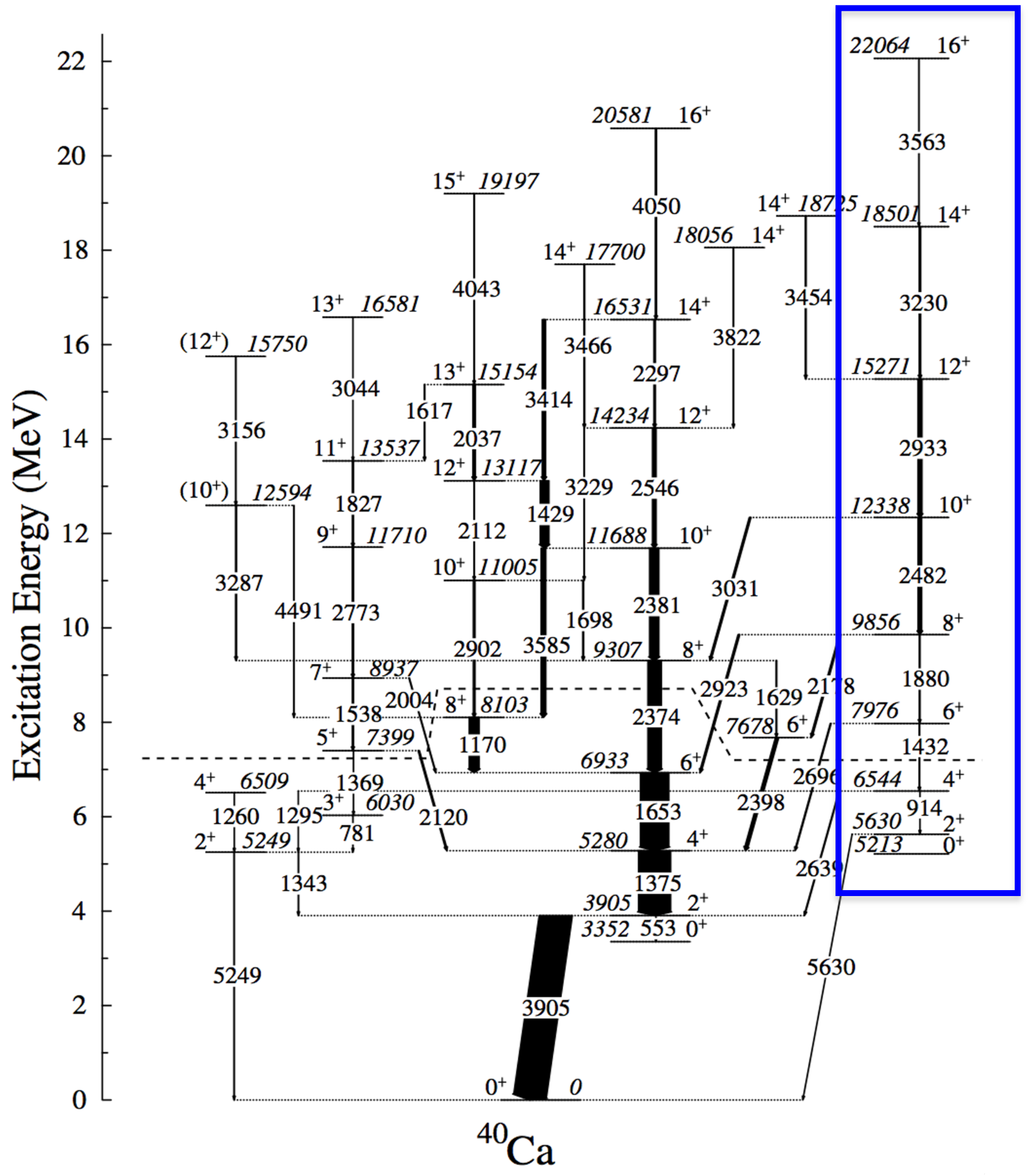
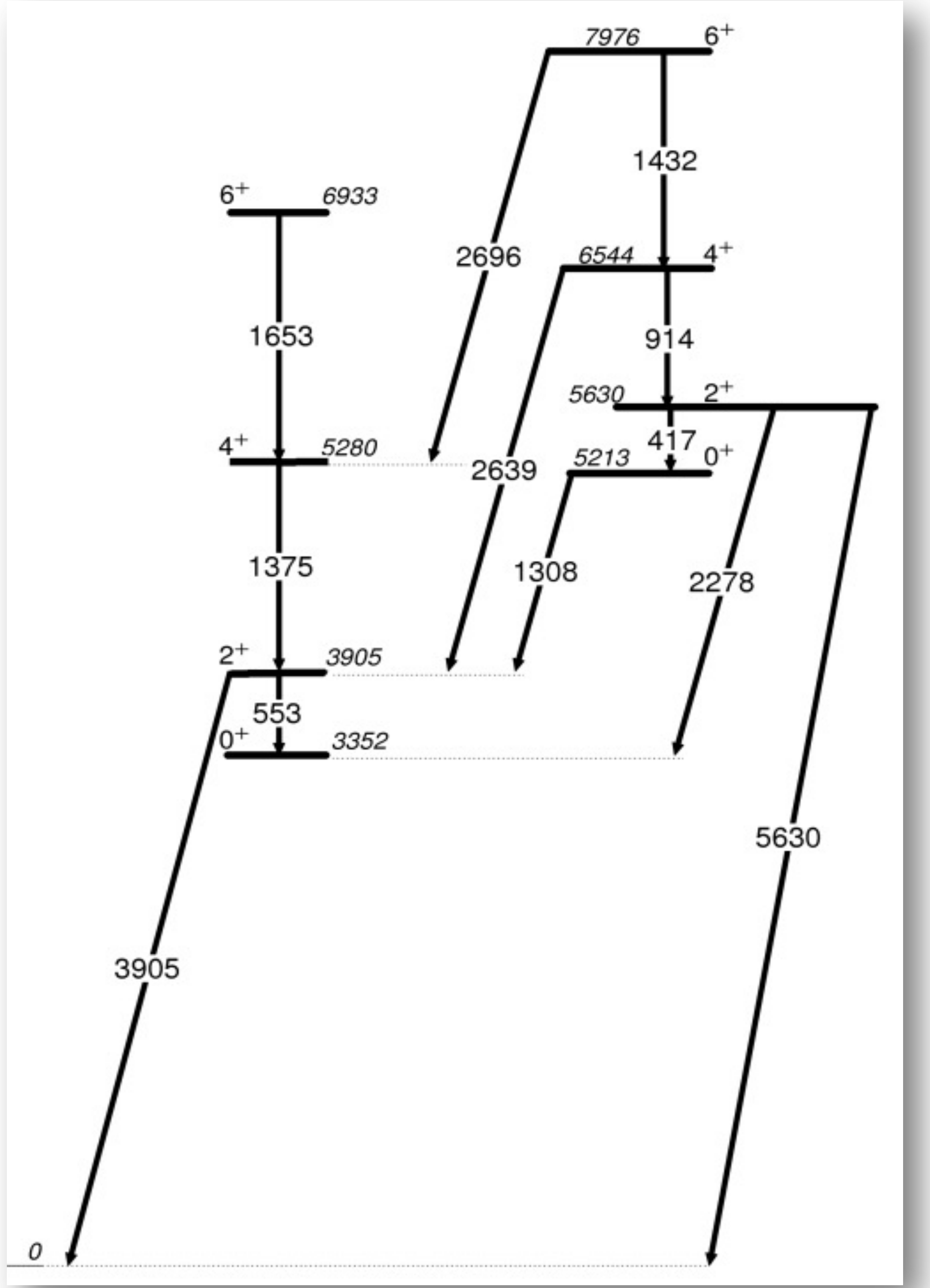
# Nuclear deformations: SD in A~40 region

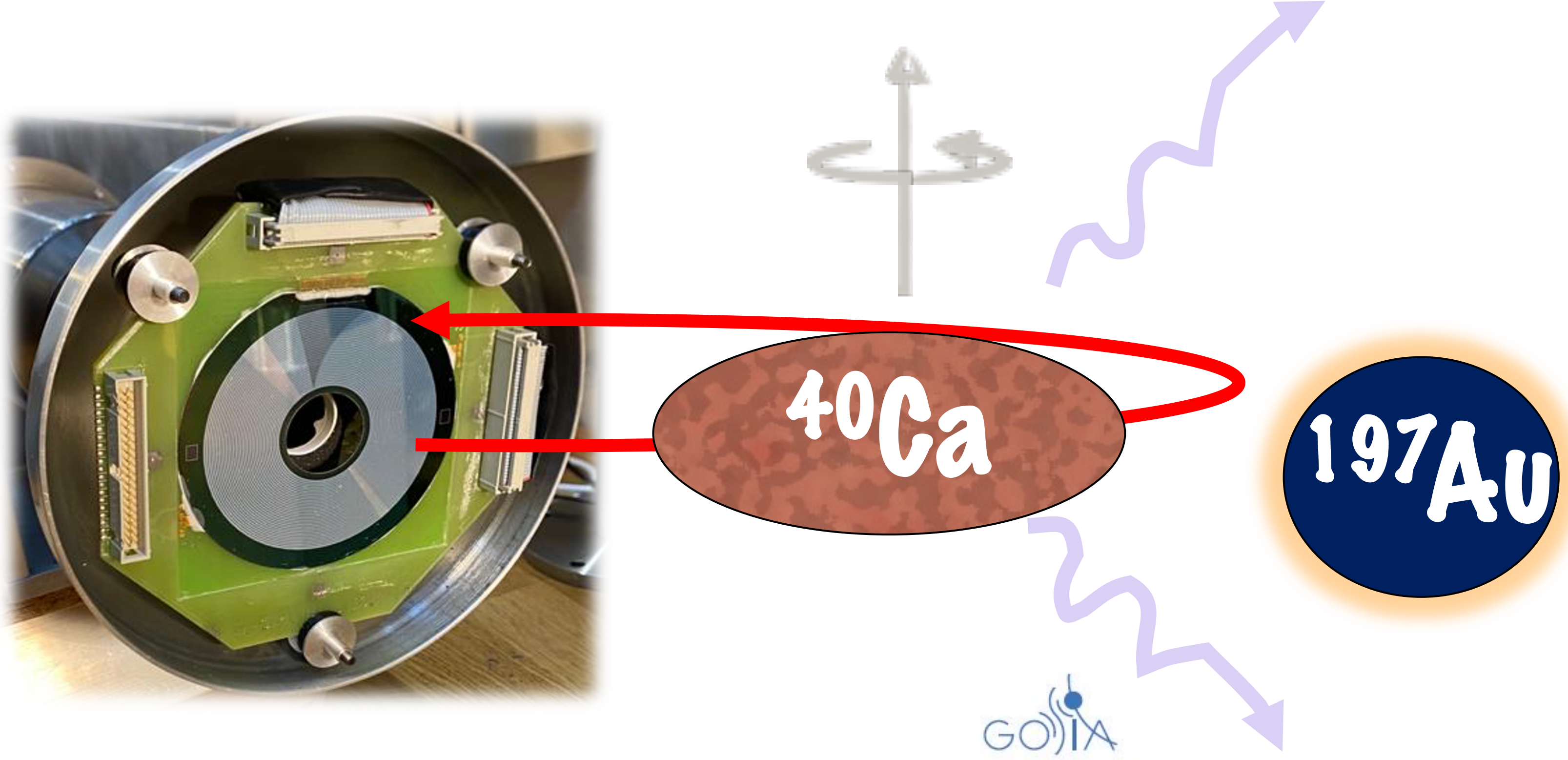


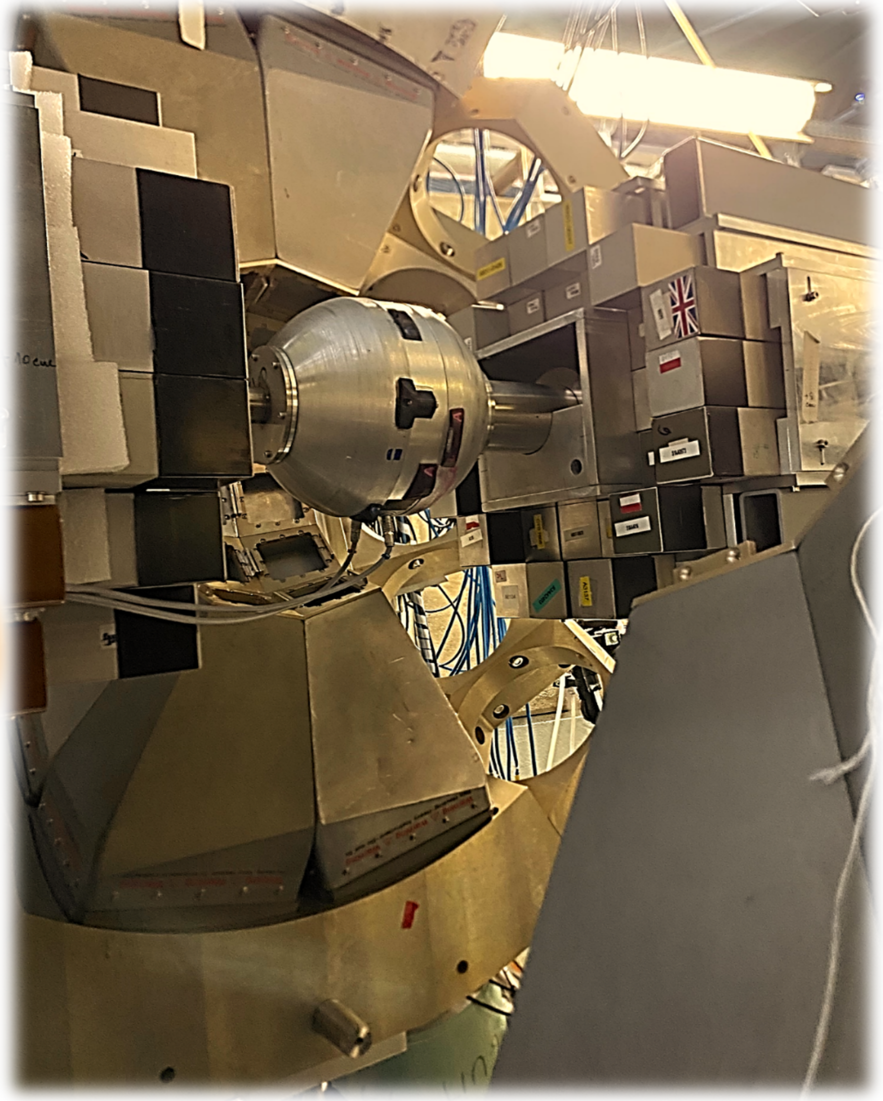

| isotope | experimental $\beta_2$ | configuration | $0^+$ energy | |
|---|---|---|---|---|
| $^{40}$Ca | $0.59^{+0.14}_{-0.11}$ | 8p-8h | 5.2 MeV | E. Ideguchi et al., PRL 81 (2001) 222501 |
| | $0.27 \pm 0.05$ | 4p-4h | 3.4 MeV | |
| $^{36}$Ar | $0.46 \pm 0.03$ | 4p-8h | 4.3 MeV | C. Svensson et al., PRL 85 (2000) 2693 |
| $^{38}$Ar | $(0.42^{+0.11}_{-0.08})$ | 4p-6h | 3.4 MeV | R. Austin, PhD thesis (2004) |
| | >0.68 | 4p-6h | 4.7 MeV | |
| $^{40}$Ar | $0.53^{+0.20}_{-0.13} \pm 0.06$ | 4p-4h | 2.1 MeV | E. Ideguchi et al., PLB 686 (2010) 18 |
| $^{44}$Ti | not known | 8p-4h | 1.9 MeV | D. O'Leary et al., PRC 61 (2000) 064314 |
| $^{42}$Ca | $0.43(4)$ $(0_2^+)$ | 6p-4h | 1.8 MeV | K. Hadyńska-Klęk, PRL 117 (2016) 062501 |
| | $0.45(4)$ $(2_2^+)$ | 6p-4h | | |


N-SI-85

# Nuclear deformations: COULEX of $^{40}$Ca (N-SI-85)

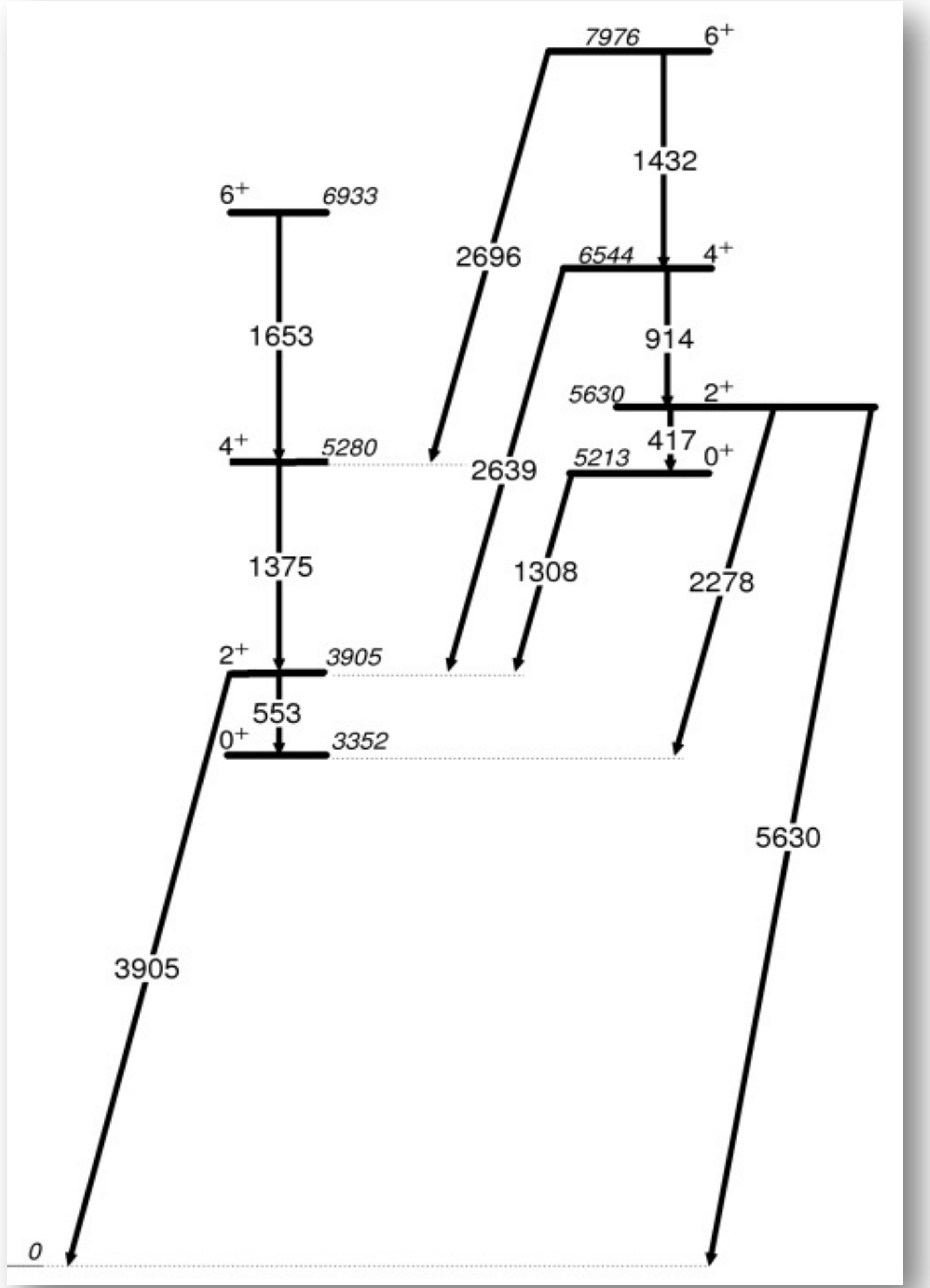


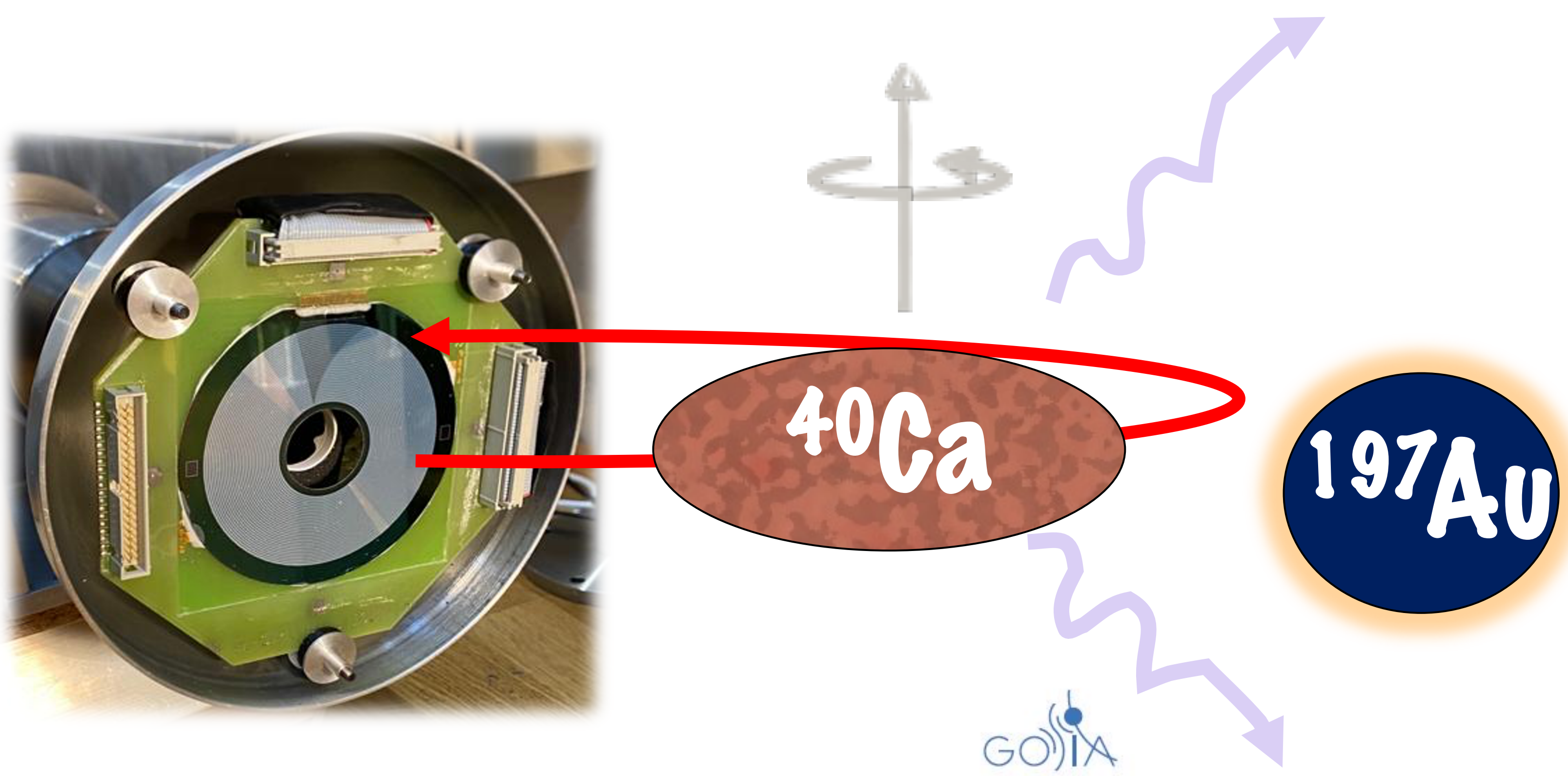



| Transition | Energy [keV] | Counts/day |
|---|---|---|
| ND band transitions | | |
| $2_1^+ \rightarrow 0_{GS}^+$ | 3905 | 115000 |
| $2_1^+ \rightarrow 0_2^+$ | 553 | 250 |
| $4_1^+ \rightarrow 2_1^+$ | 1375 | 8500 |
| $6_1^+ \rightarrow 4_1^+$ | 1653 | 250 |
| SD band transitions | | |
| $2_{SD}^+ \rightarrow 0_{SD}^+$ | 417 | 200 |
| $4_{SD}^+ \rightarrow 2_{SD}^+$ | 914 | 1200 |
| $6_{SD}^+ \rightarrow 4_{SD}^+$ | 1432 | 50 |
| SD$\rightarrow$ND transitions | | |
| $0_{SD}^+ \rightarrow 2_1^+$ | 1308 | 70000 |
| $2_{SD}^+ \rightarrow 0_2^+$ | 2278 | 4000 |
| $2_{SD}^+ \rightarrow 2_1^+$ | 1725 | 1500 |
| $2_{SD}^+ \rightarrow 0_{GS}^+$ | 5630 | 17000 |
| $4_{SD}^+ \rightarrow 2_1^+$ | 2639 | 2500 |
| $4_{SD}^+ \rightarrow 4_1^+$ | 1264 | 70 |

# Nuclear deformations: COULEX of $^{40}Ca$ (N-SI-85)




GOSIA

| Transition | Energy [keV] | Counts/day |
|---|---|---|
| **ND band transitions** | | |
| $2_1^+ \rightarrow 0_{GS}^+$ | 3905 | 115000 |
| $2_1^+ \rightarrow 0_2^+$ | 553 | 250 |
| $4_1^+ \rightarrow 2_1^+$ | 1375 | 8500 |
| $6_1^+ \rightarrow 4_1^+$ | 1653 | 250 |
| **SD band transitions** | | |
| $2_{SD}^+ \rightarrow 0_{SD}^+$ | 417 | 200 |
| $4_{SD}^+ \rightarrow 2_{SD}^+$ | 914 | 1200 |
| $6_{SD}^+ \rightarrow 4_{SD}^+$ | 1432 | 50 |
| **SD→ND transitions** | | |
| $0_{SD}^+ \rightarrow 2_1^+$ | 1308 | 70000 |
| $2_{SD}^+ \rightarrow 0_2^+$ | 2278 | 4000 |
| $2_{SD}^+ \rightarrow 2_1^+$ | 1725 | 1500 |
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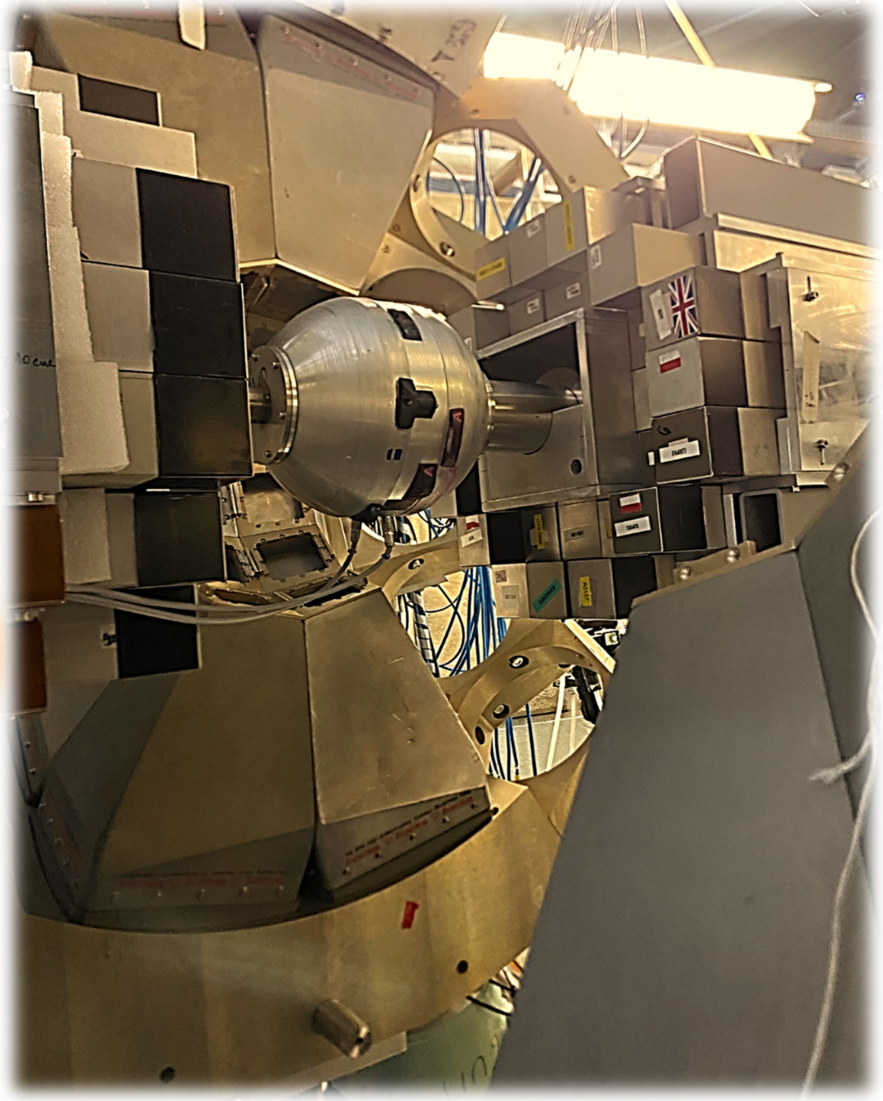
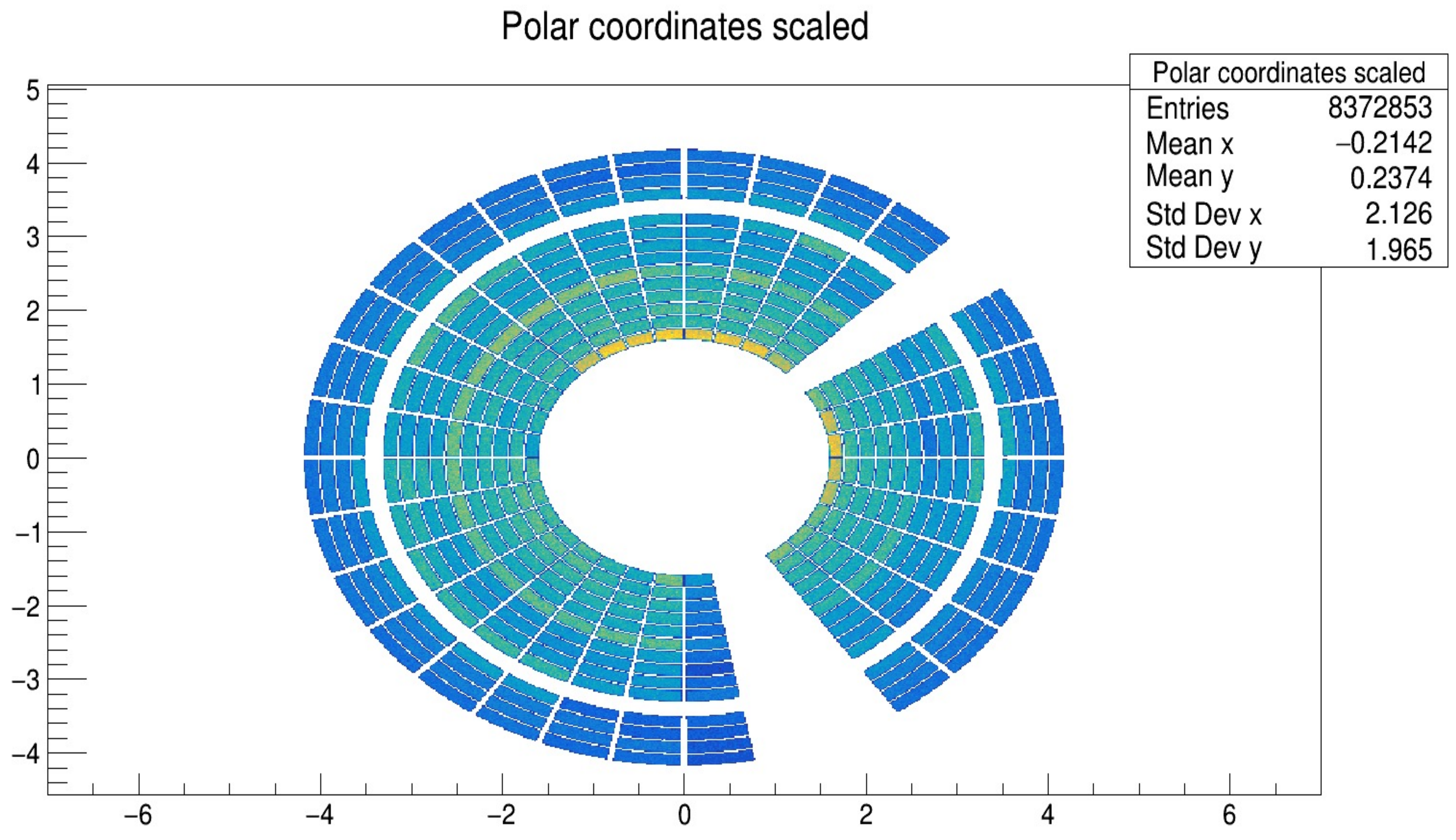
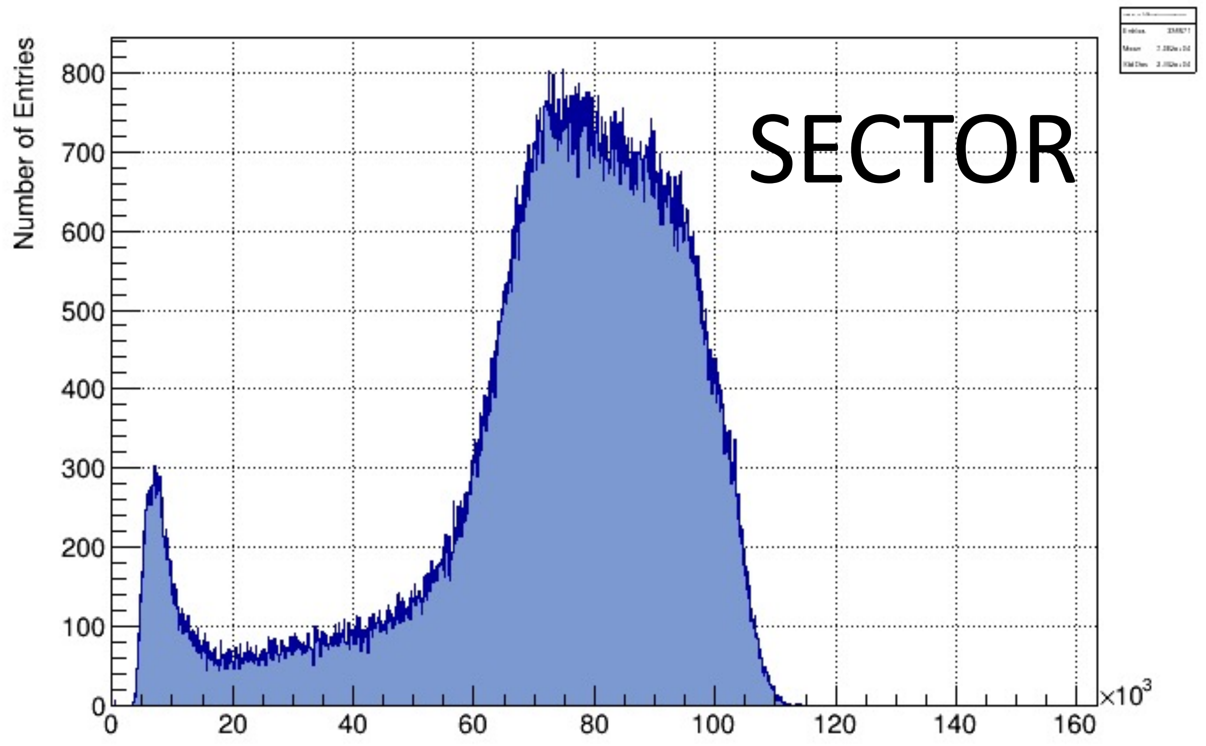
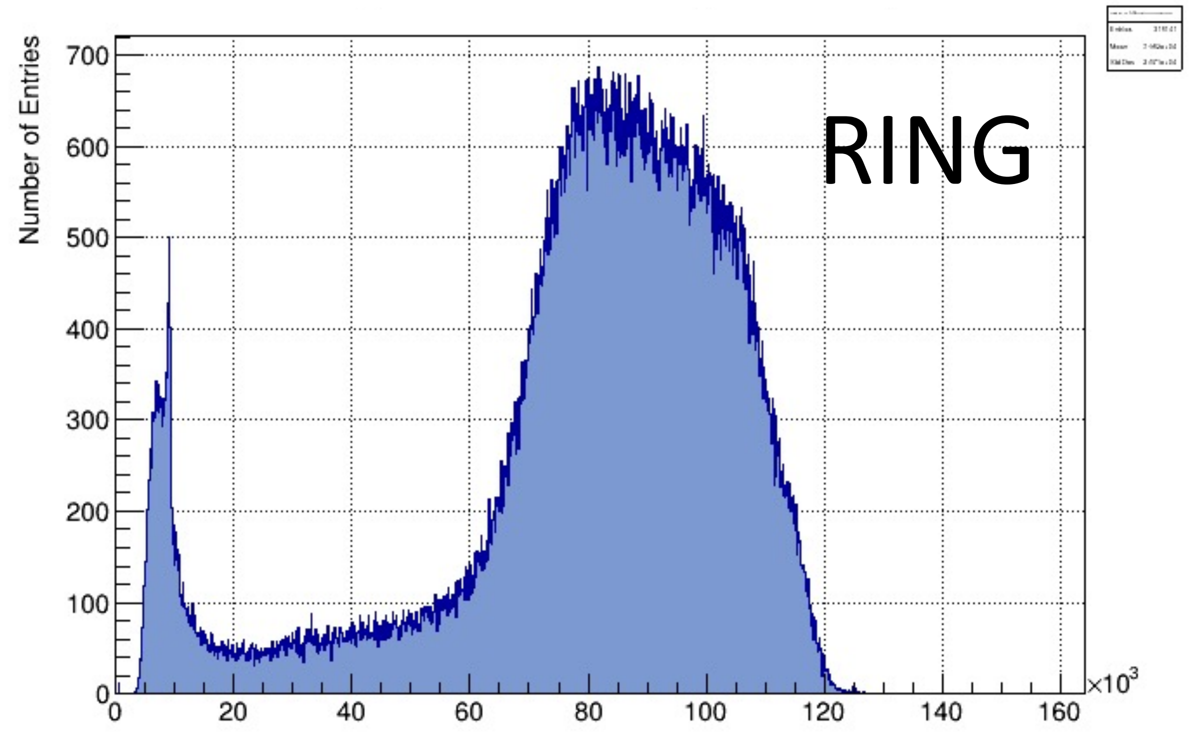
| $4_{SD}^+ \rightarrow 2_1^+$ | 2639 | 2500 |
| $4_{SD}^+ \rightarrow 4_1^+$ | 1264 | 70 |



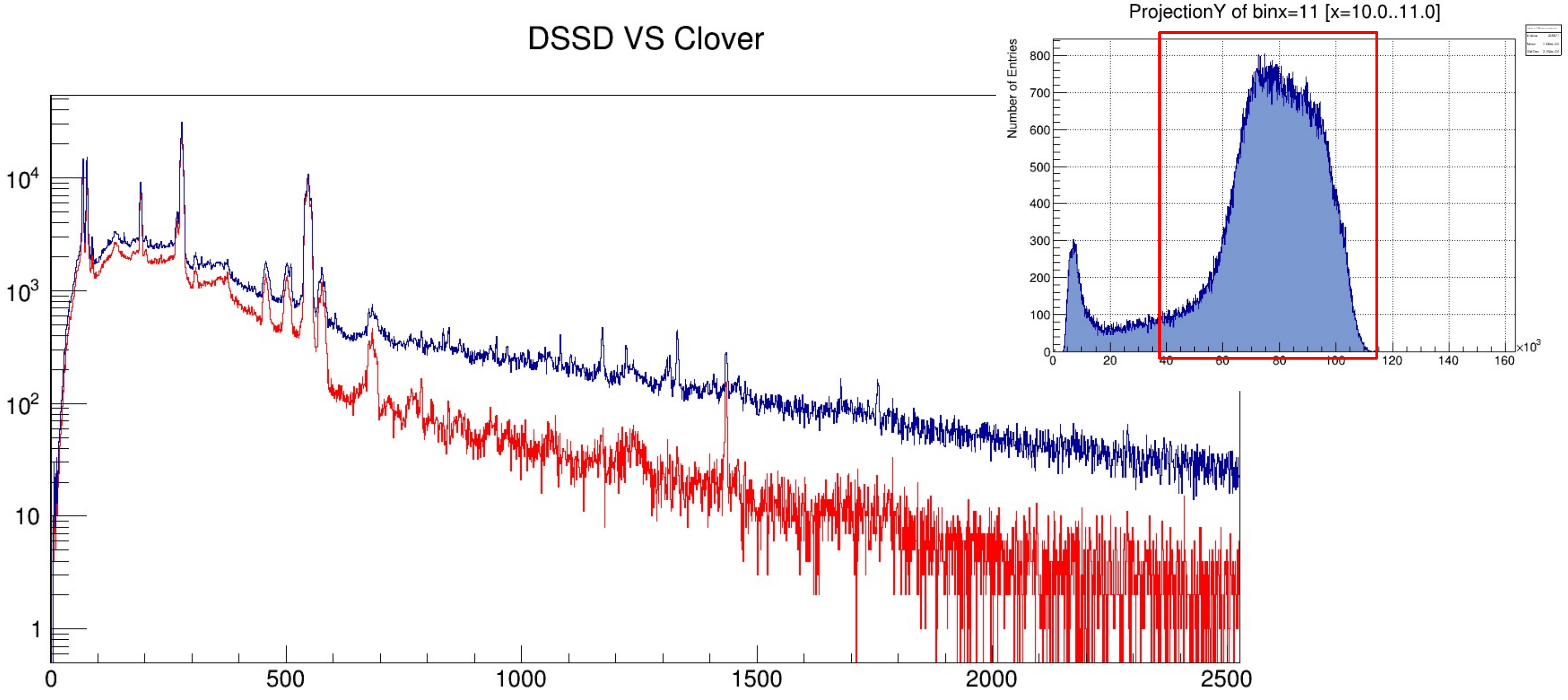
# COULEX of $^{40}Ca$ – DSSD spectra



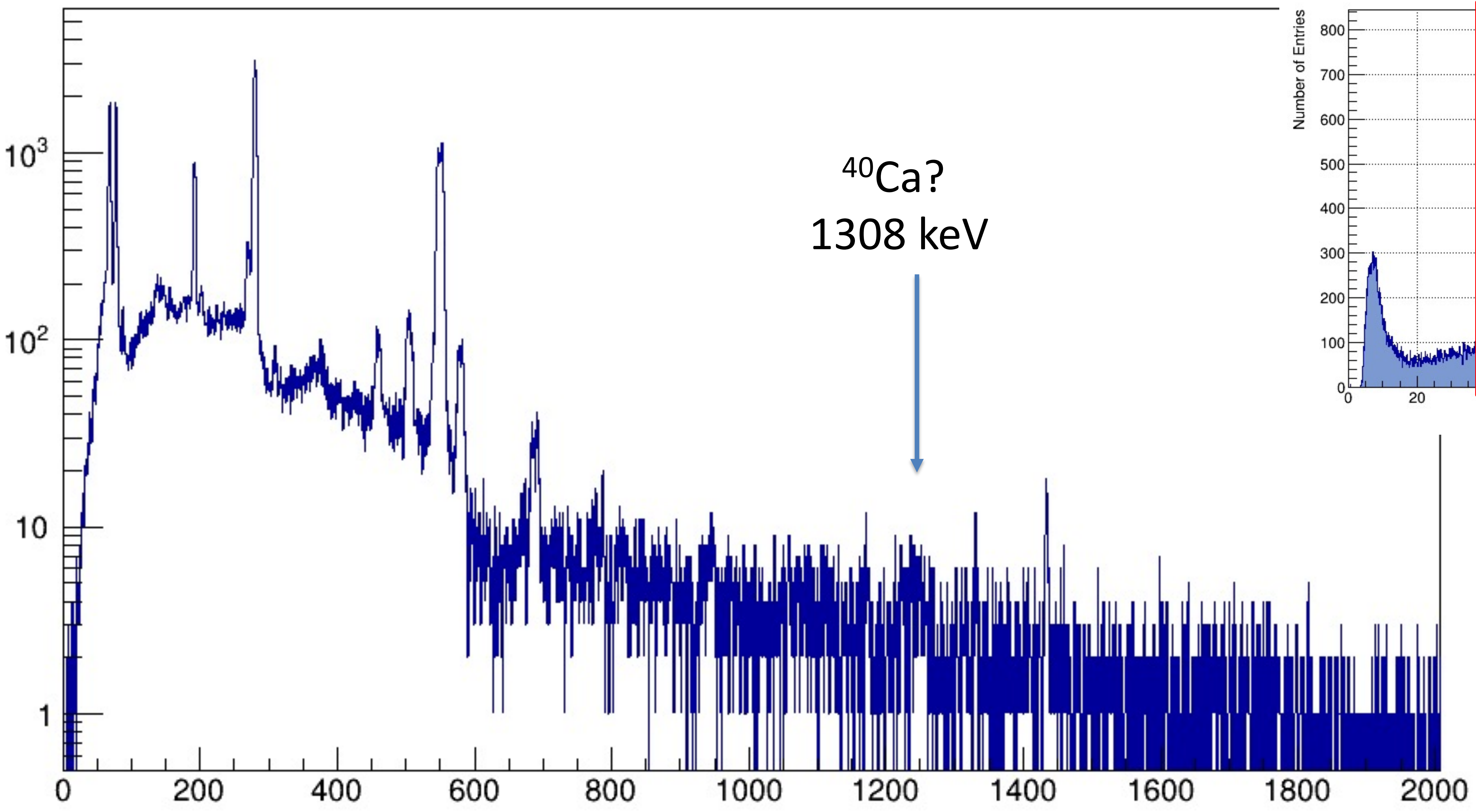



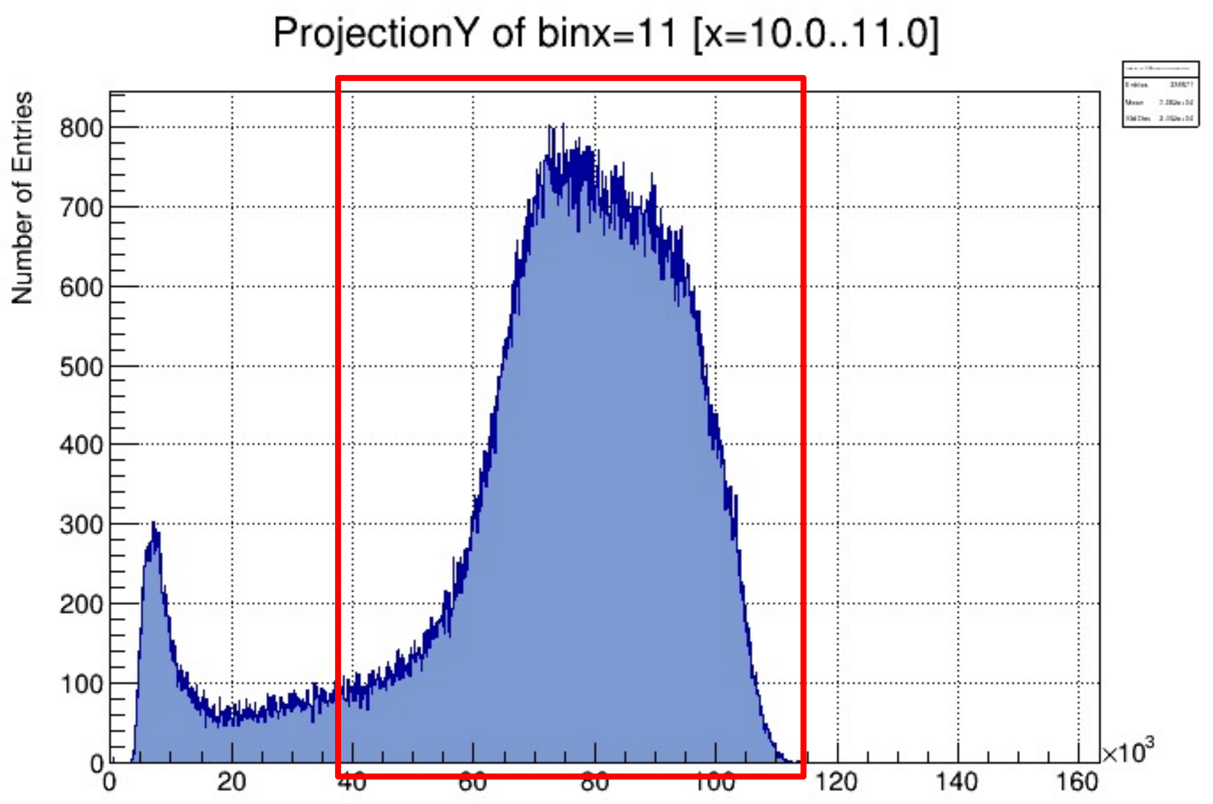



# COULEX of $^{40}Ca$ – selection based on the DSSD



# COULEX of $^{40}$Ca - preliminary (av. Doppler Correction)



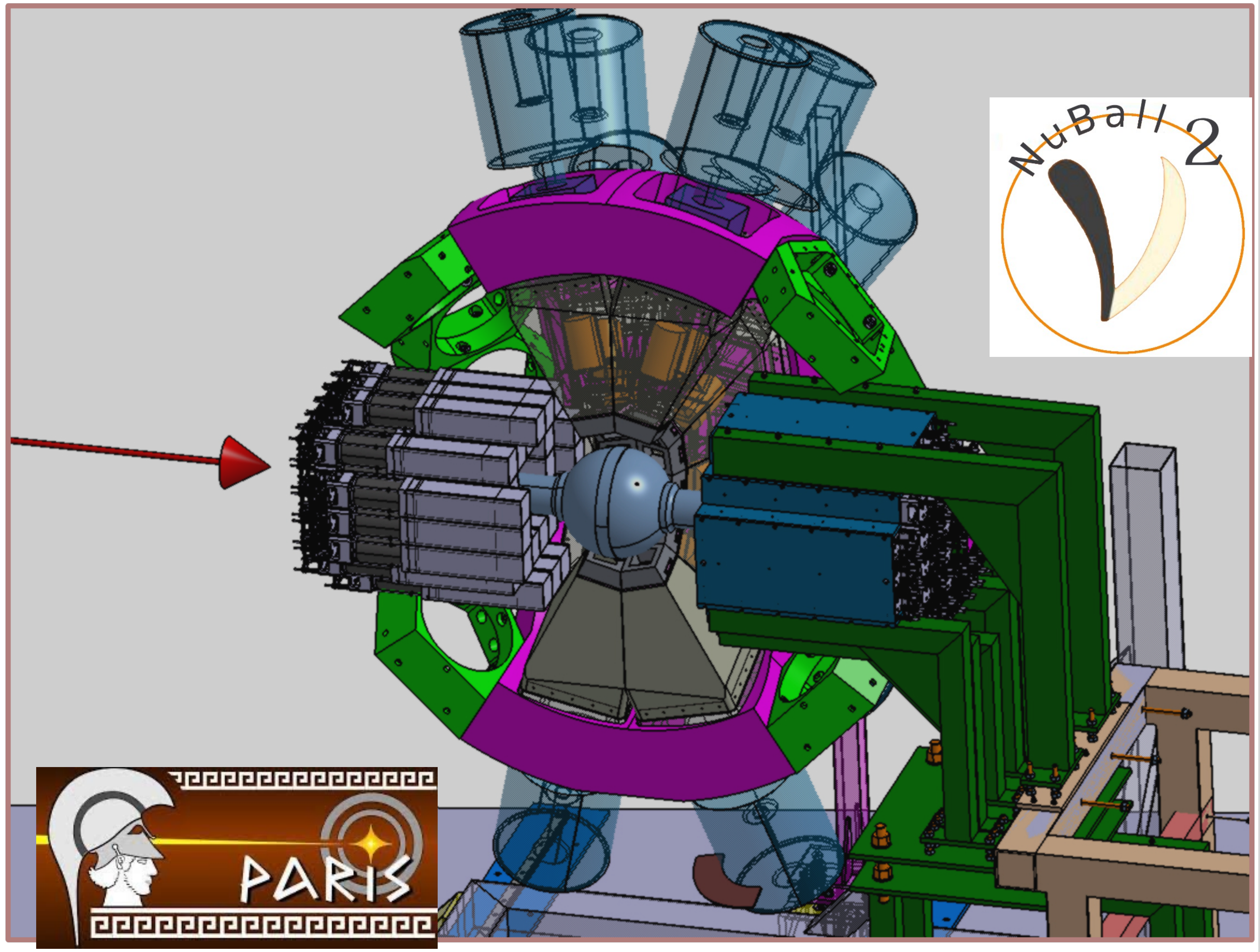

2 days of the data taking only

Analysis is ongoing

# Experimental campaign: IJC Lab, Orsay

**Spring 2023**

- ✓ *Search for the fission shape isomer in $^{232}$Th*
  spokesperson and data analysis: C. Hiver
- ✓ *$^{194,196}$Hg fission studies*
  spokesperson and data analysis: K. Miernik
- ❑ *Investigation of high spin structures in $^{44}$Ti and $^{42}$Ca via discrete and continuum gamma spectroscopy using nuBall2, PARIS and OPSA setup*
  spokespersons: M. Matejska-Minda, K. Hadyńska-Klęk
  data analysis: M. Matejska-Minda
- ✓ ***Emergence of collectivity near magic nuclei: Coulomb-excitation of $^{62}$Ni*    (* $^{60}$Ni)***
  spokespersons: : K. Hadyńska-Klęk, M. Rocchini, N. Marchini
  data analysis: K. Hadyńska-Klęk

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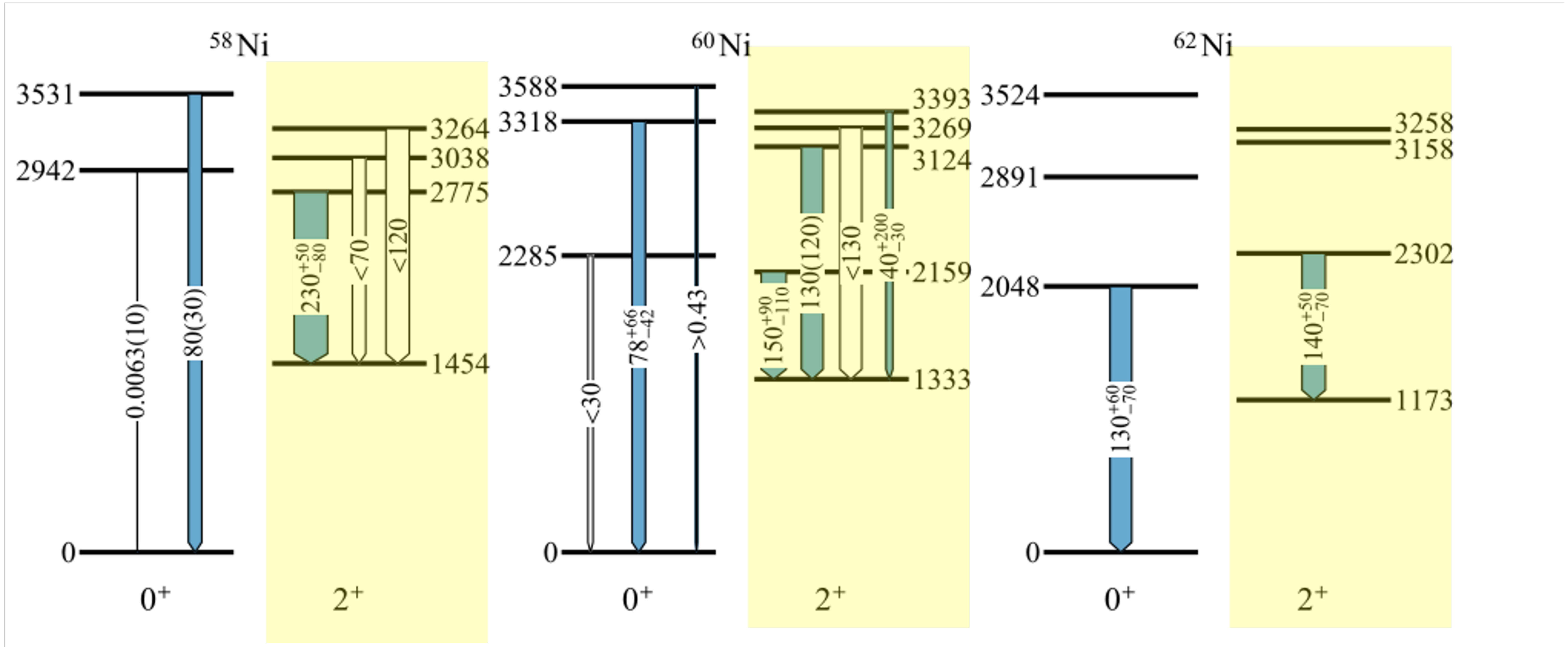
# Extremes of the E0 - Ni chain

L.J. Evitts et al., Phys. Rev. C 99 (2019) 024306.




The largest $\rho^2(2_2^+ \to 2_1^+)$ values in medium and heavy nuclei reported to date

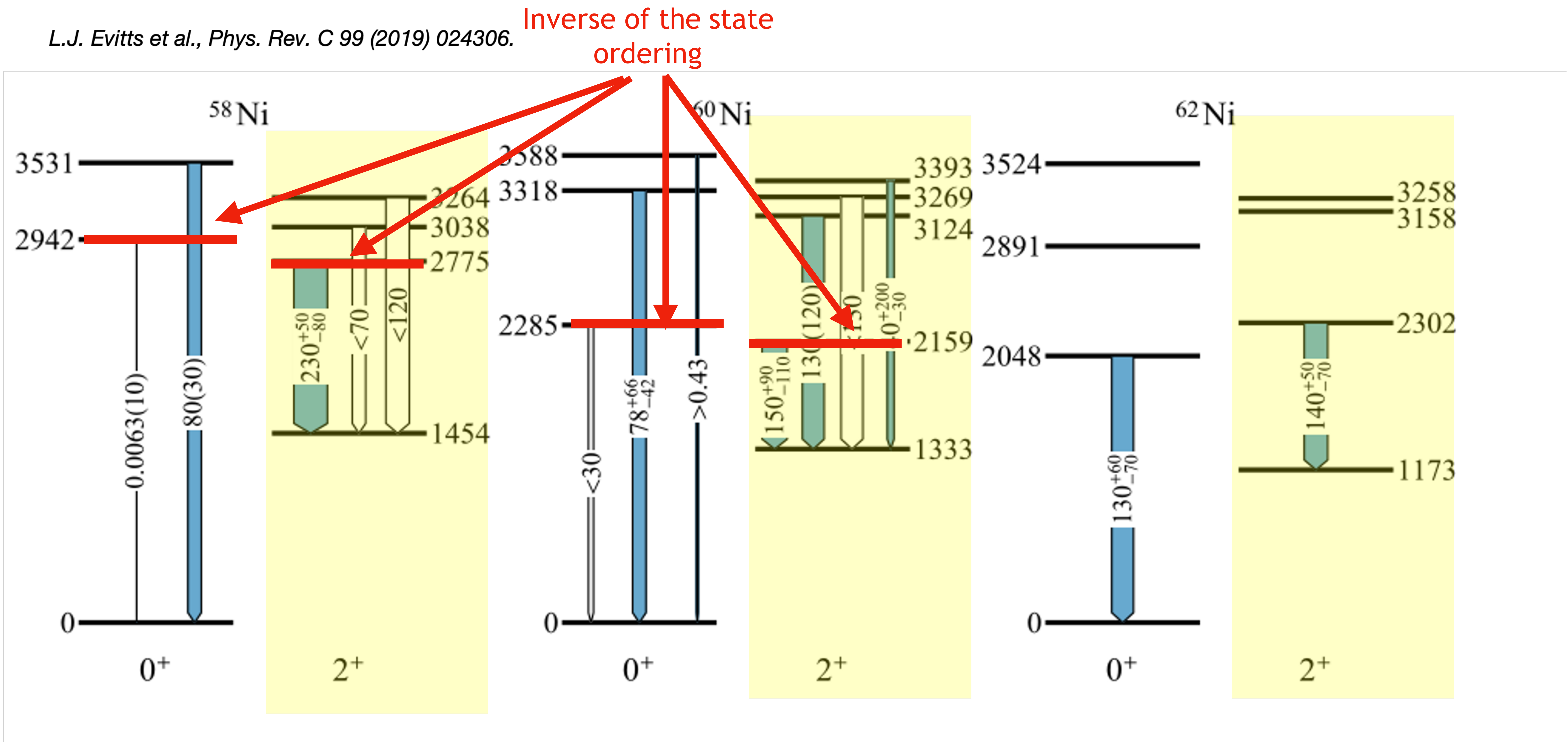
BREAKING the vibrational picture

A spherical vibrator - the E0 transitions are forbidden if the change in phonon number is one

$2_2^+$CANNOT BE a 2ν STATE

# Extremes of the E0 – Ni chain

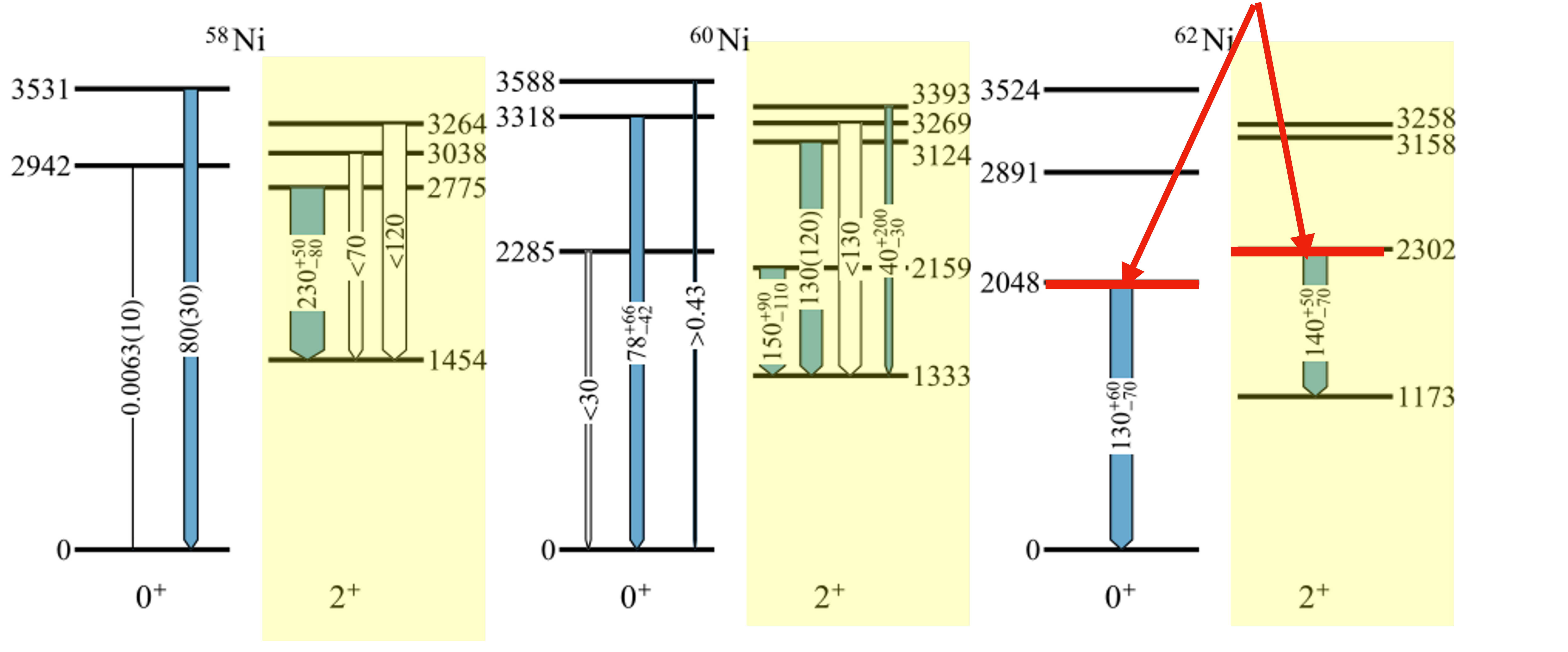
*L.J. Evitts et al., Phys. Rev. C 99 (2019) 024306.*



# Extremes of the E0 - Ni chain

*L.J. Evitts et al., Phys. Rev. C 99 (2019) 024306.*

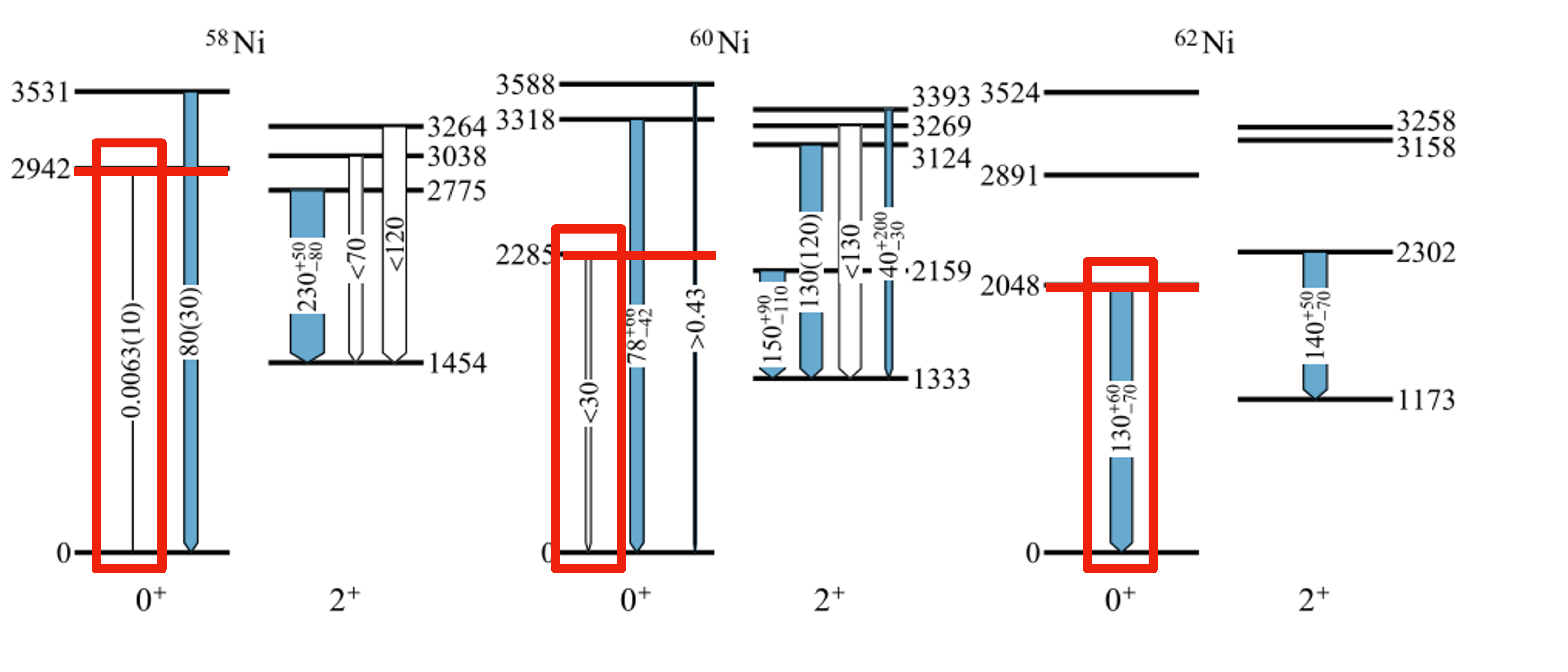
Sudden change of ordering - change of structure



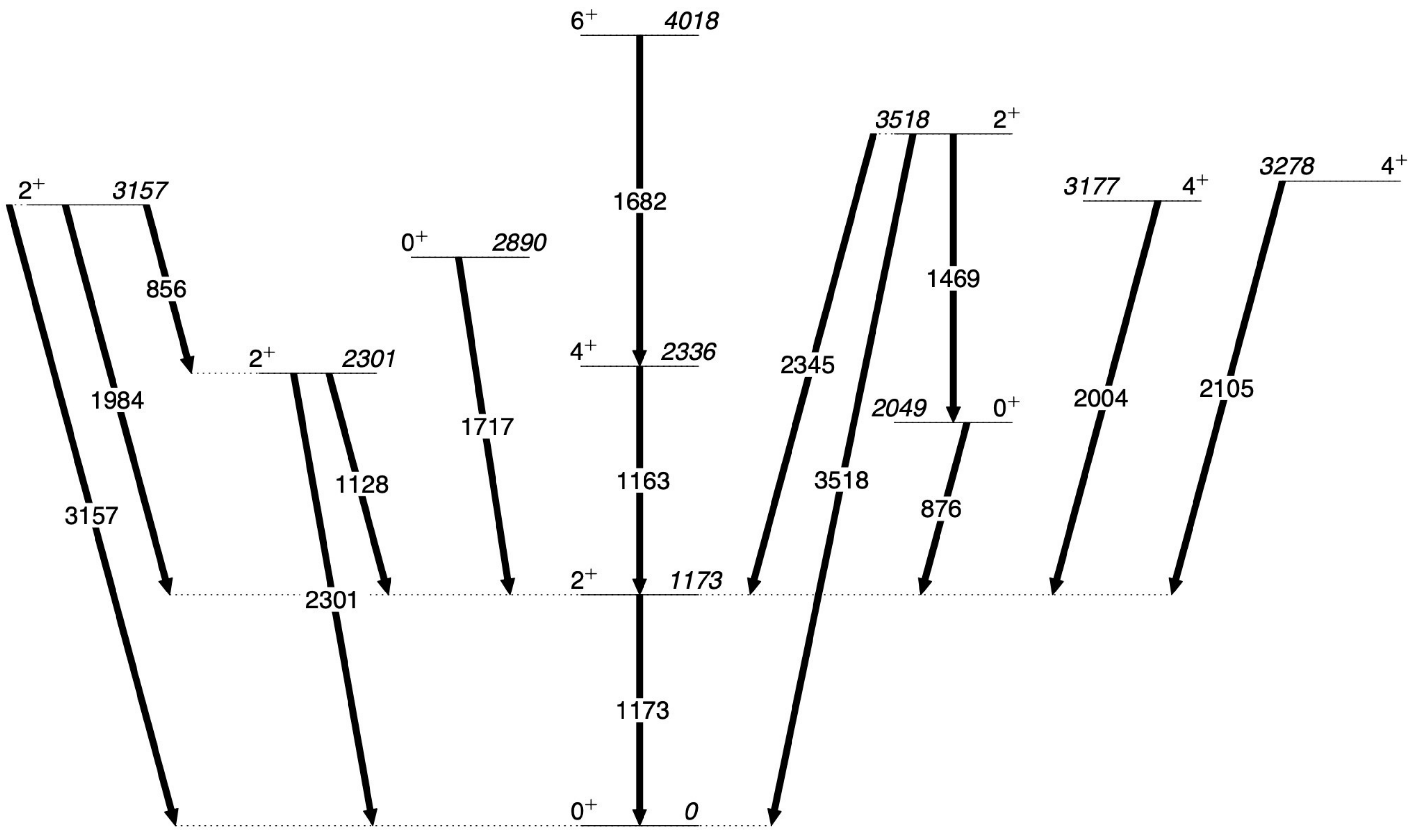
# Extremes of the E0 – Ni chain

*L.J. Evitts et al., Phys. Rev. C 99 (2019) 024306.*

Increasing B(E0) between $0^+$ states with the N number



# Nuclear collectivity: COULEX of $^{62}$Ni

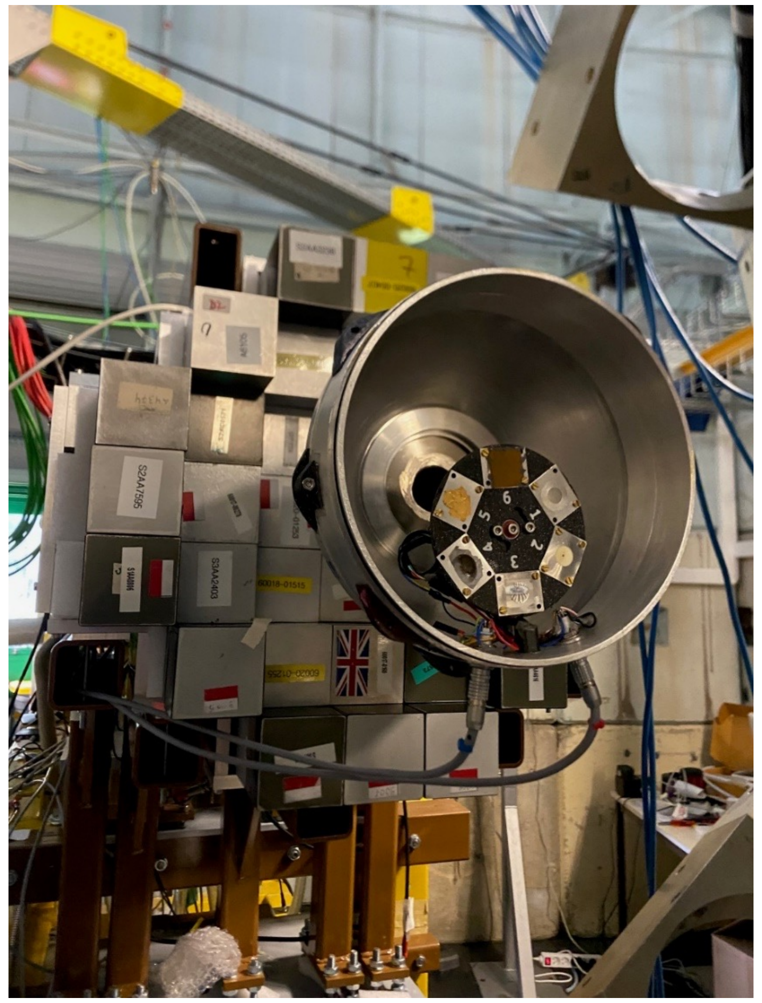


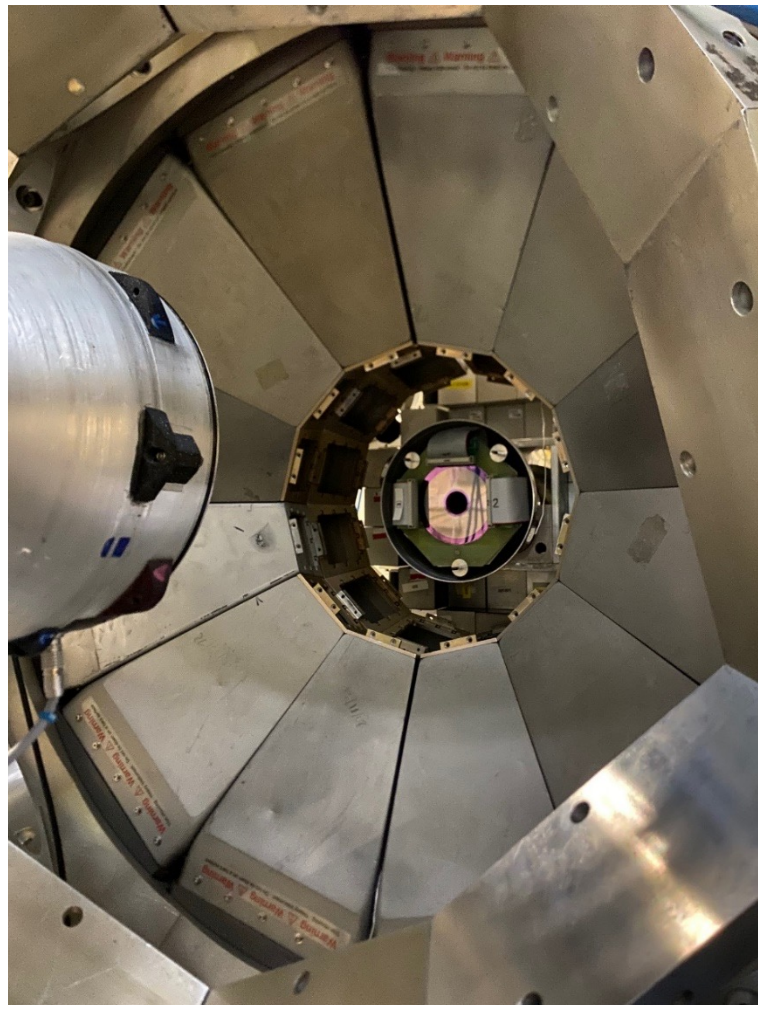

N-SI-137

- $^{62}$Ni beam, 233 MeV, 1 pnA
- $^{208}$Pb target, 1 mg/cm2
- 7 days of data taking requested
- DSSD (127-154o) + NUBALL2 (4% at 1.3 MeV)

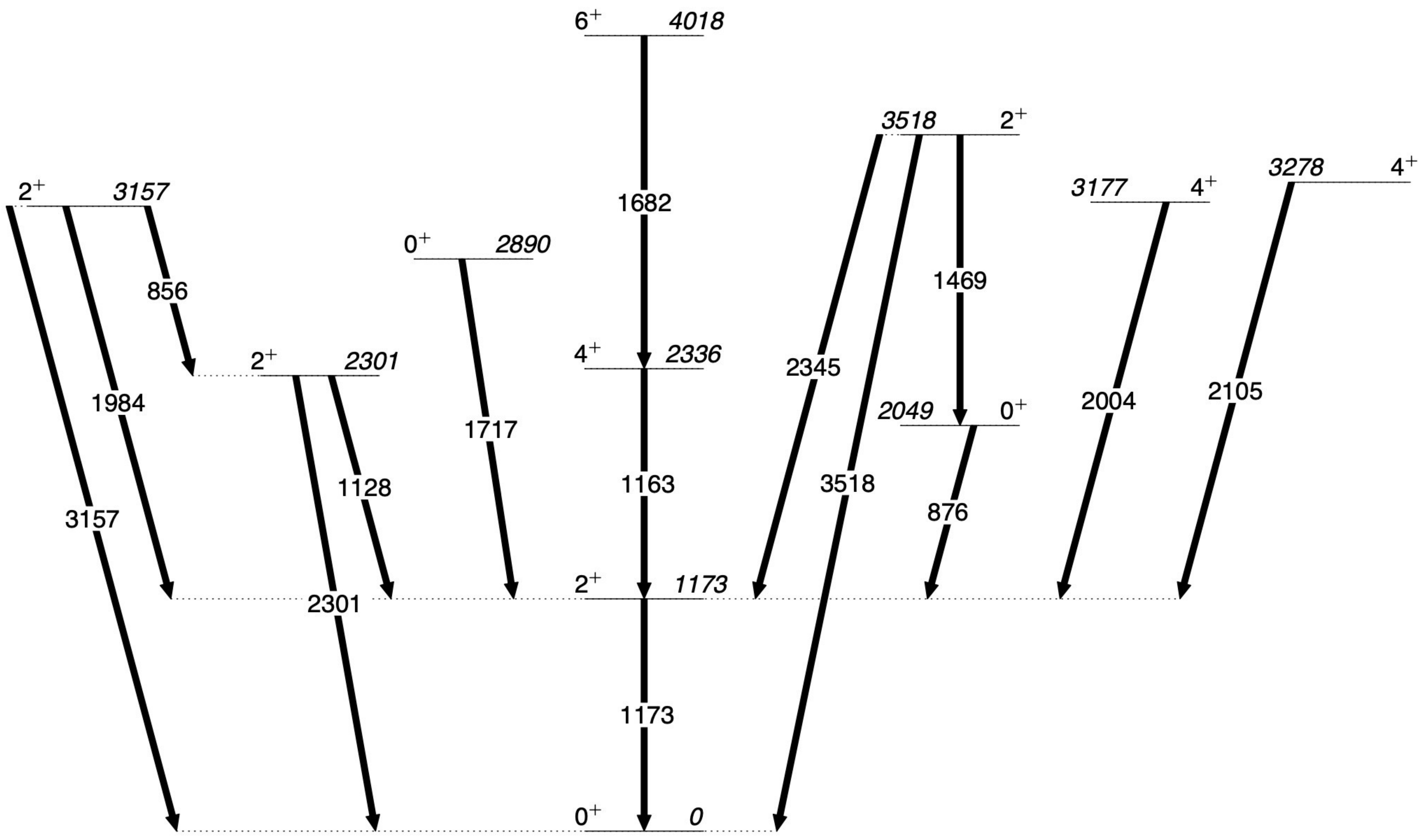
**<u>Proposal accepted</u>**

**Scheduled: 15-23.06**





# Nuclear collectivity: COULEX of $^{62}$Ni

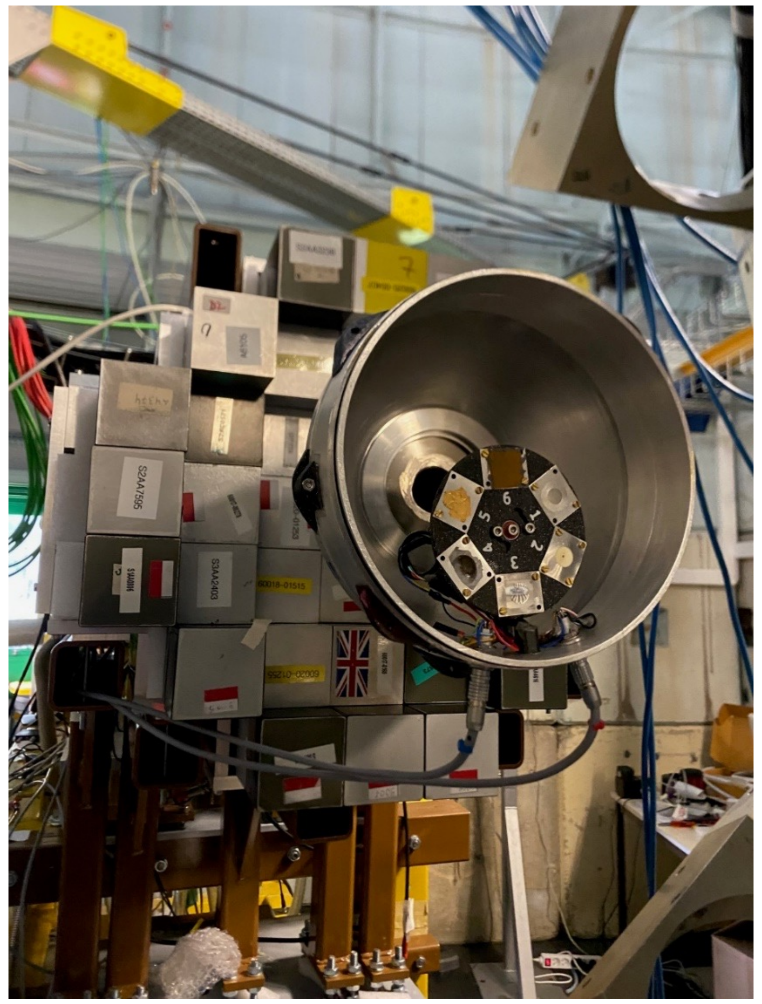


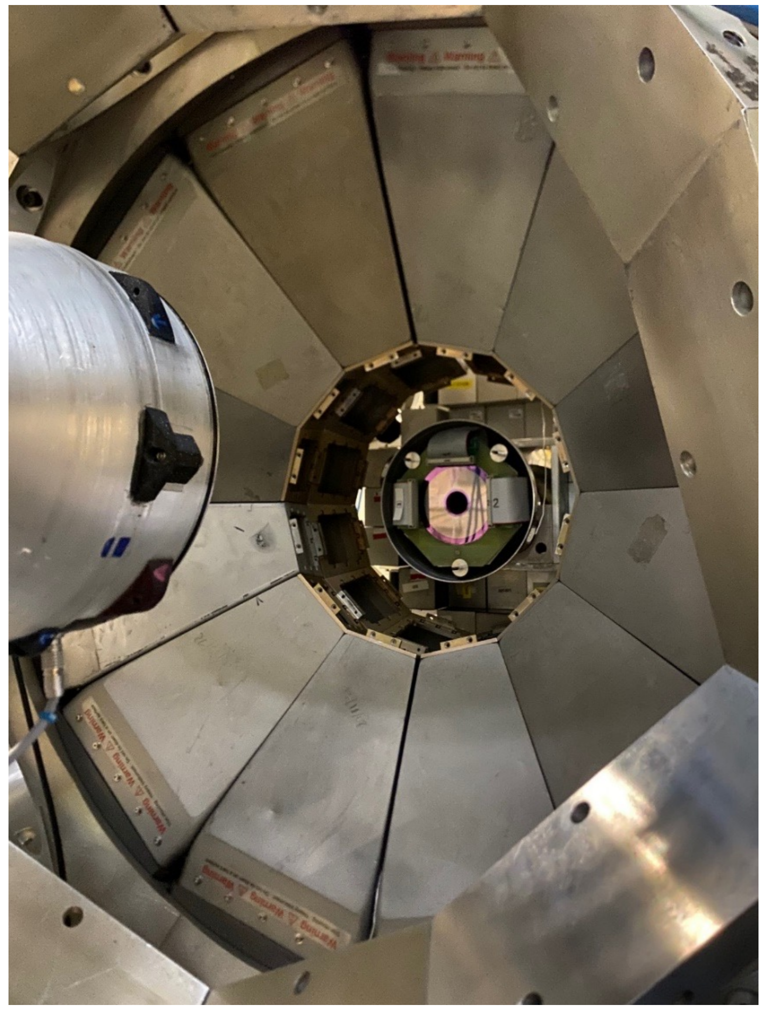

- Start was OK
- Then many unexpected issues with the beam
- Unstable, sparks… even with the lover E
- We decided to change the beam to 60Ni

- $^{62}$Ni beam, 233 MeV, 1 pnA
- $^{208}$Pb target, 1 mg/cm2
- 7 days of data taking requested
- DSSD (127-154$^{o}$) + NUBALL2 (4% at 1.3 MeV)

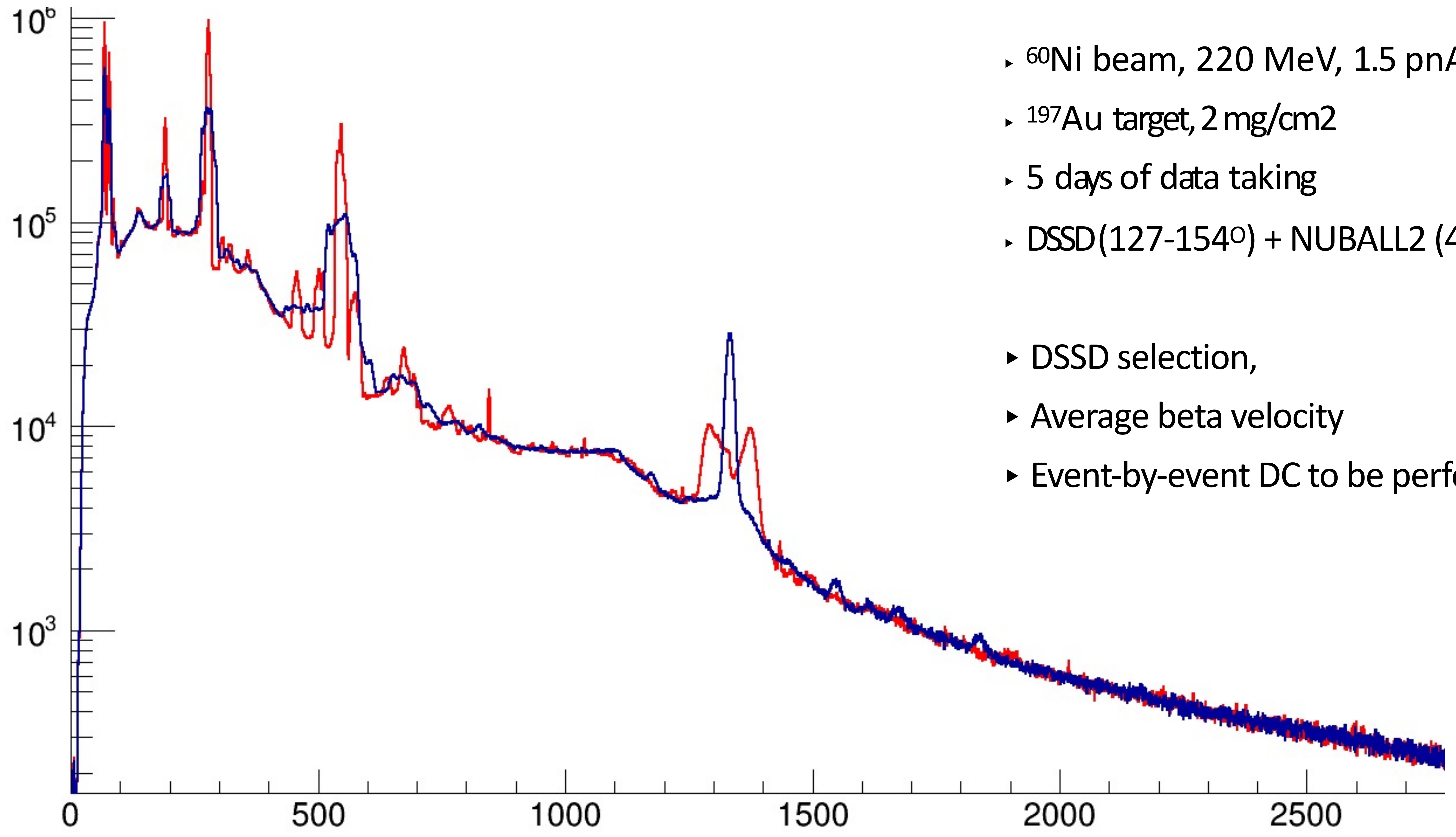
**<u>Proposal accepted</u>**

**Scheduled: 15-23.06**





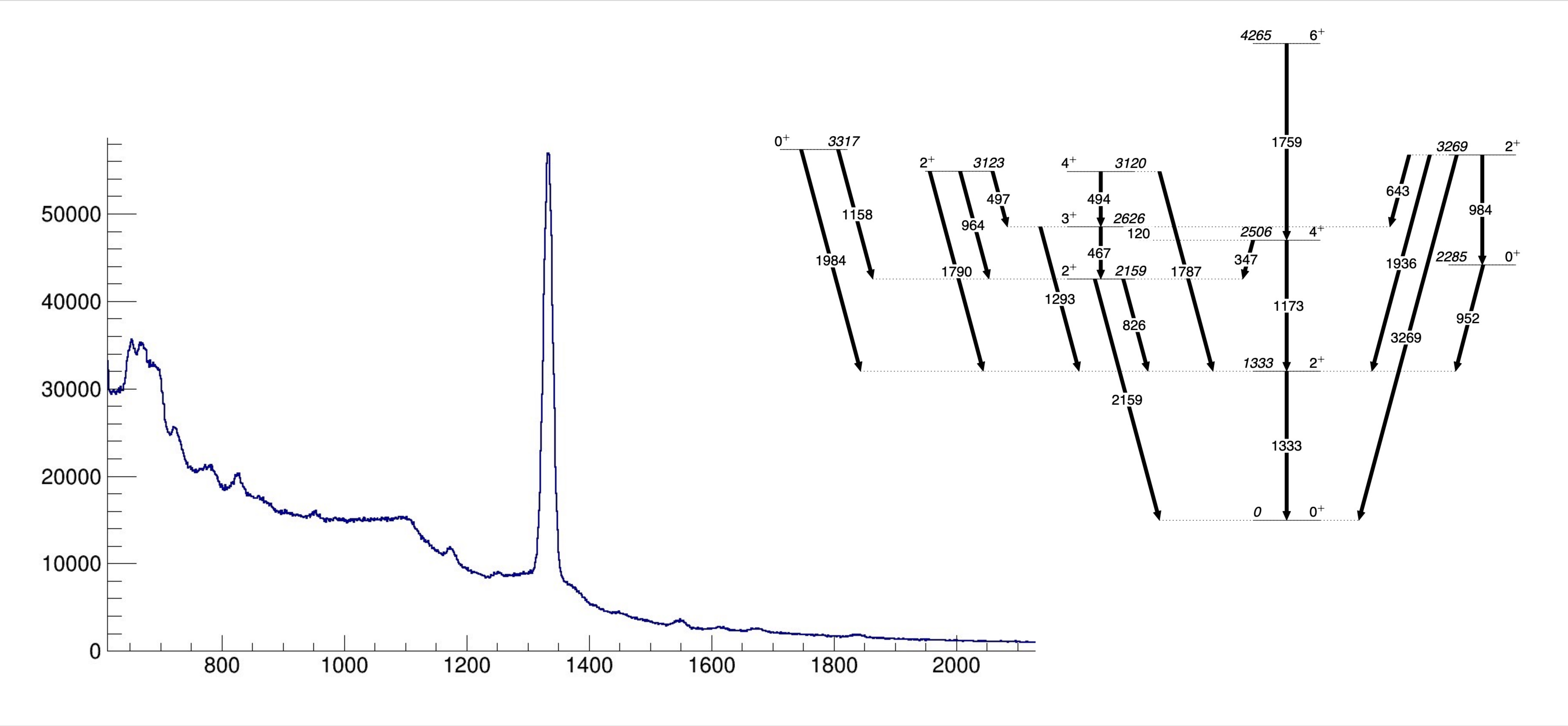
# COULEX of $^{60}$Ni - spectra with and without DC



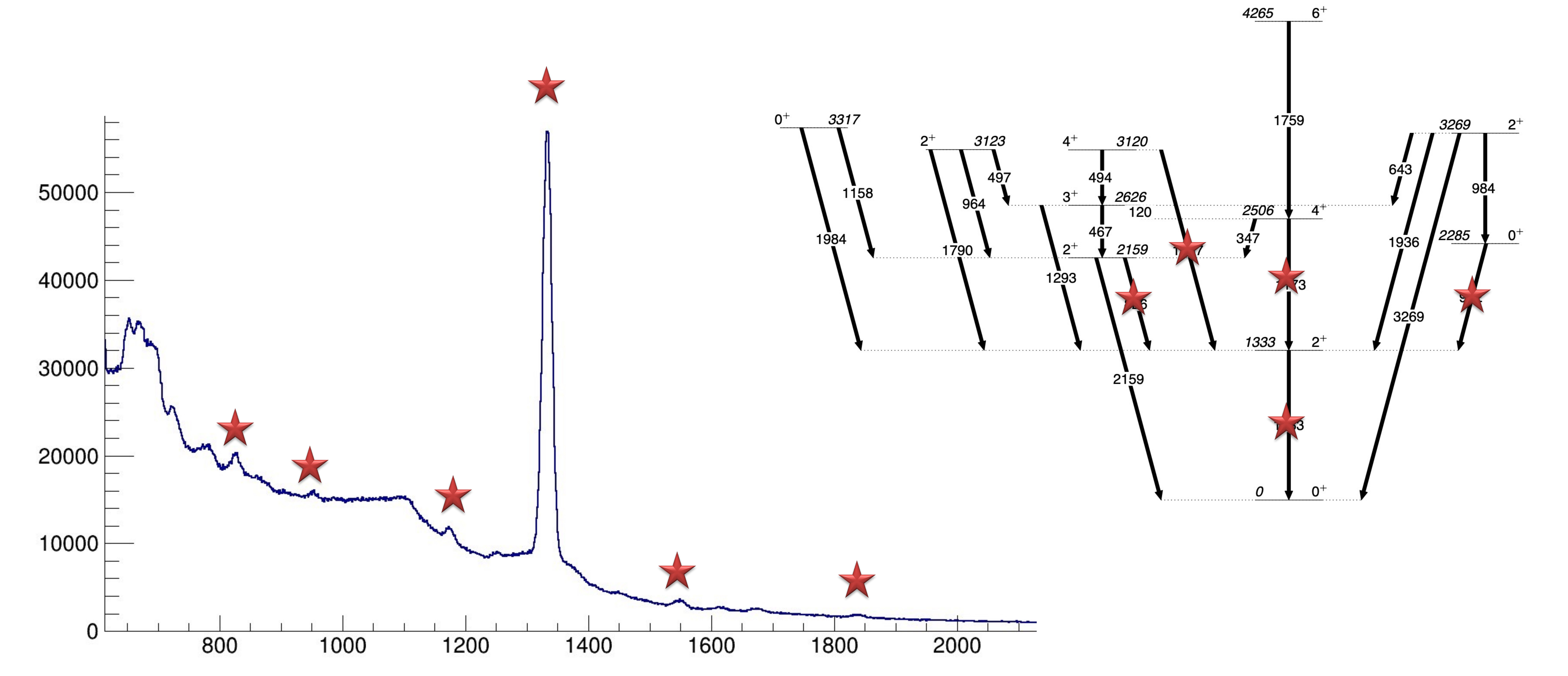

- $^{60}$Ni beam, 220 MeV, 1.5 pnA
- $^{197}$Au target, 2 mg/cm2
- 5 days of data taking
- DSSD (127-154$^{O}$) + NUBALL2 (4% at 1.3 MeV)

- DSSD selection,
- Average beta velocity
- Event-by-event DC to be performed

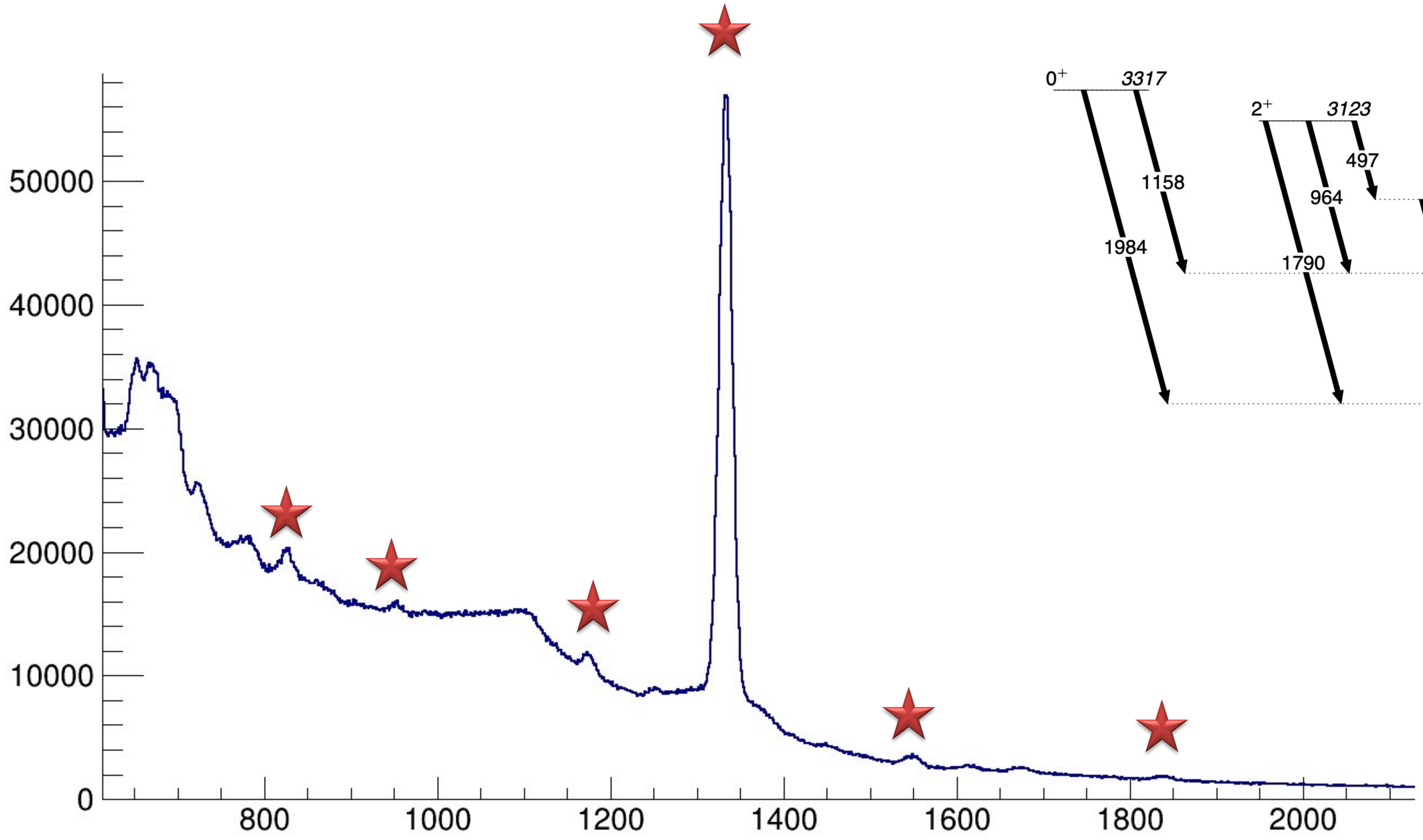
# COULEX of $^{60}$Ni – preliminary gamma spectrum (DC)

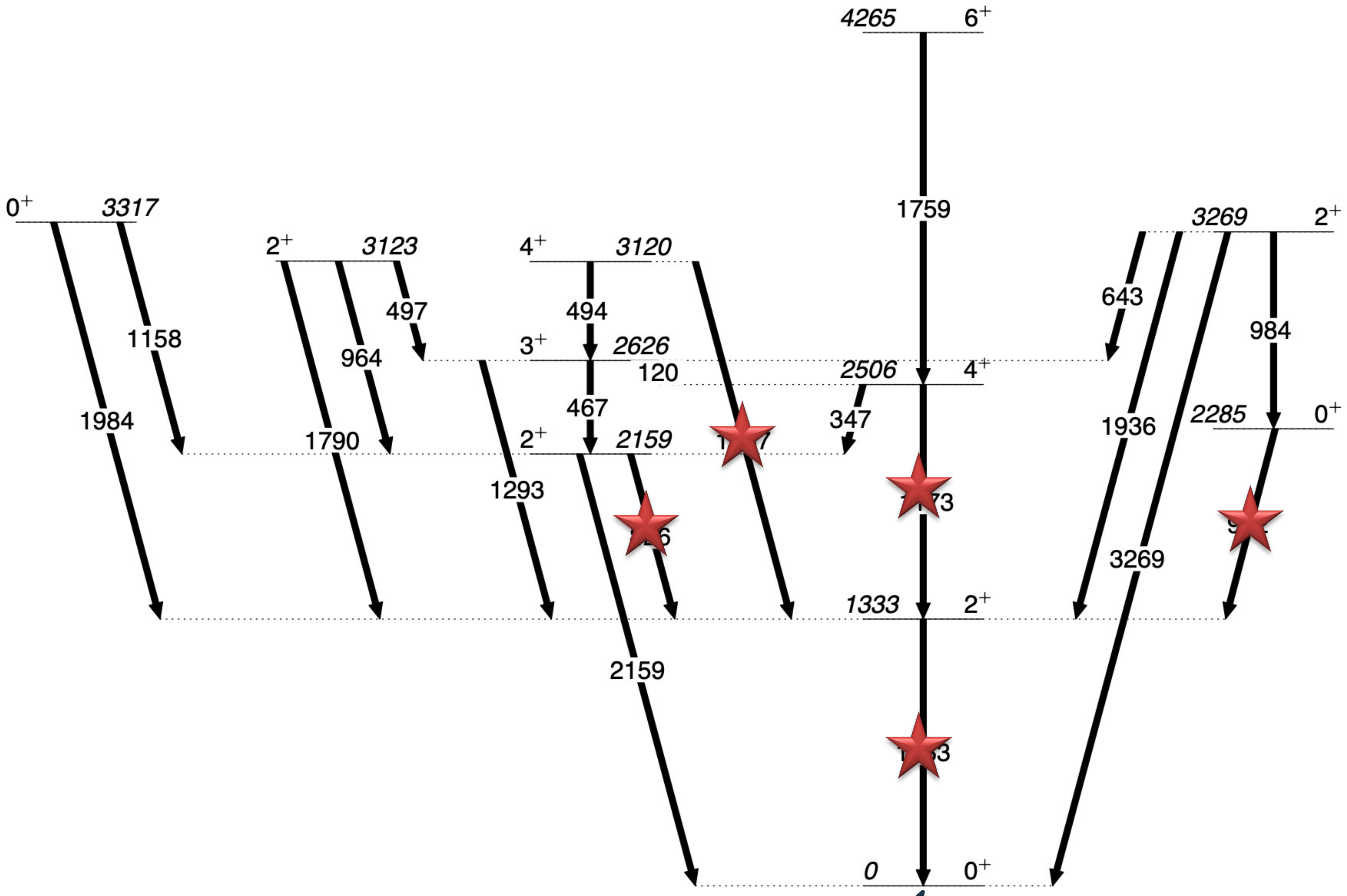


# COULEX of $^{60}Ni$ – preliminary gamma spectrum (DC)



# COULEX of $^{60}$Ni - preliminary gamma spectrum (DC)




Other transitions? Better DC needed

# Experimental campaign
(J. Wilson)

# Experimental campaign: IJC Lab, Orsay

**Winter 2022-2023**

✓ ***Detailed spectroscopy of fission isomers in uranium isotopes***

spokesperson J. Wilson

data analysis C. Hiver

✓ ***Evidence for enhanced collectivity in $^{58}Fe$ examined through Coulomb excitation***

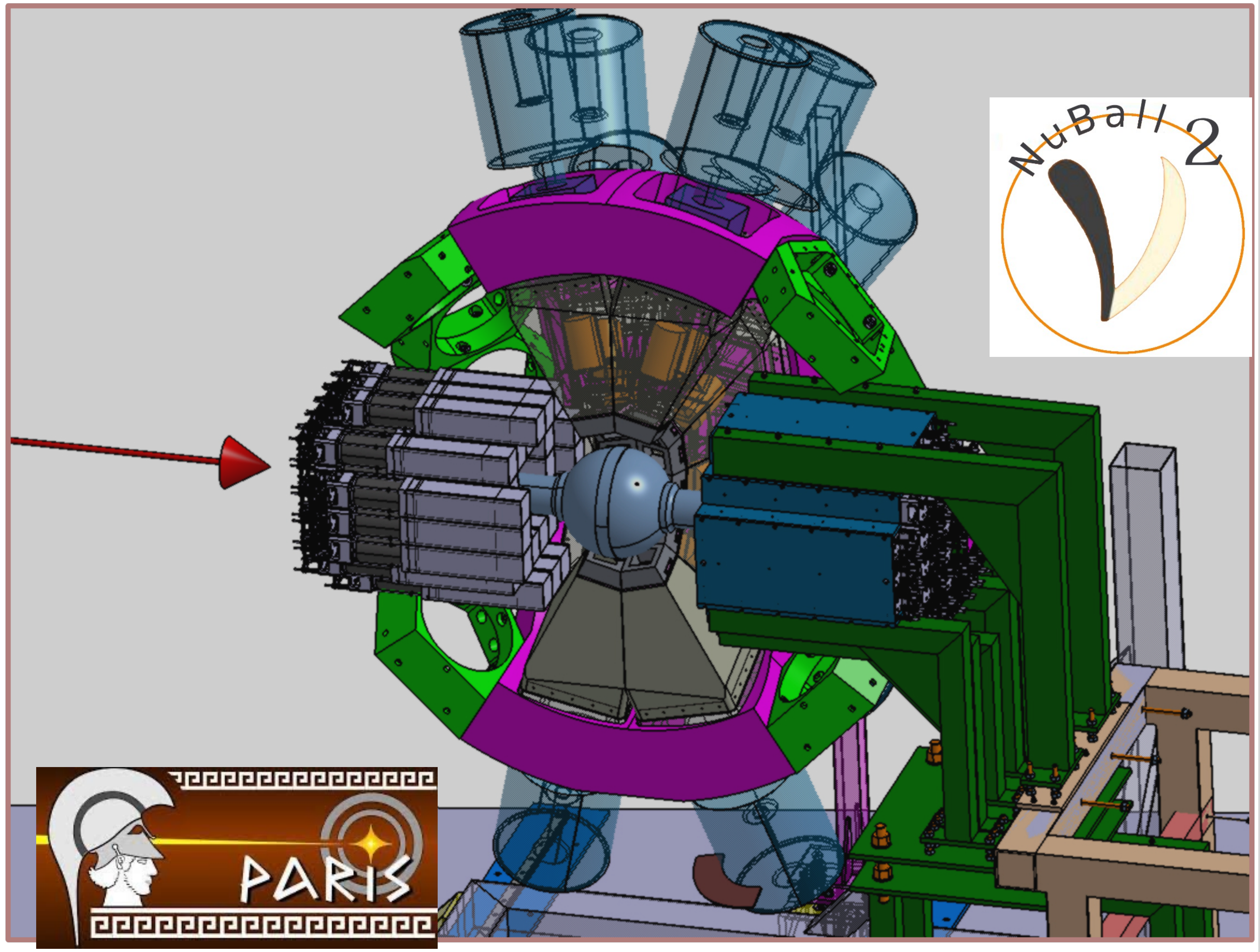
spokespersons: G. Pasqualato, J. Ljungvall, A. Stuchbery

data analysis G. Pasqualato

❑ ***Coulomb excitation of super-deformed band in $^{40}Ca$***

spokespersons: P. Napiorkowski, A. Maj, F. Azaiez

data analysis: K. Hadyńska-Klęk, J. Samorajczyk-Pyśk



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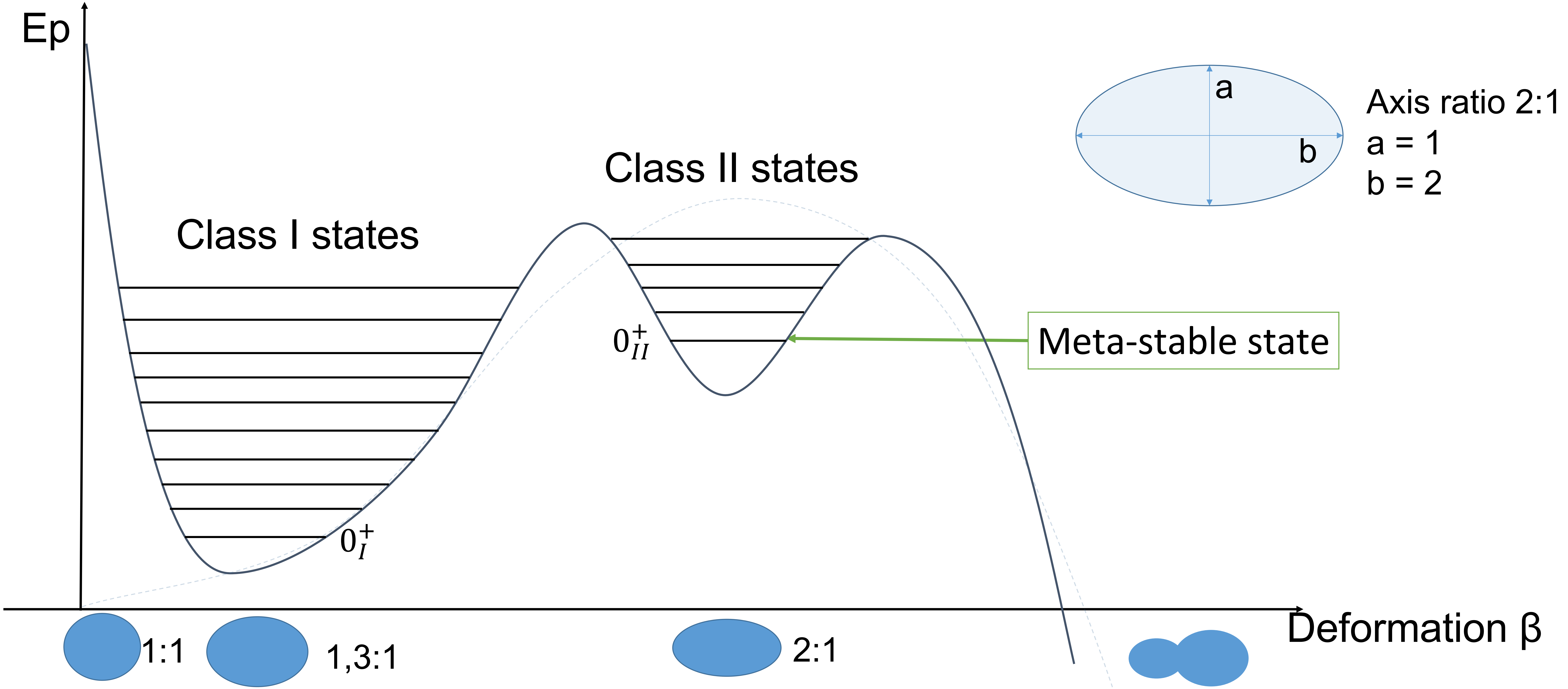
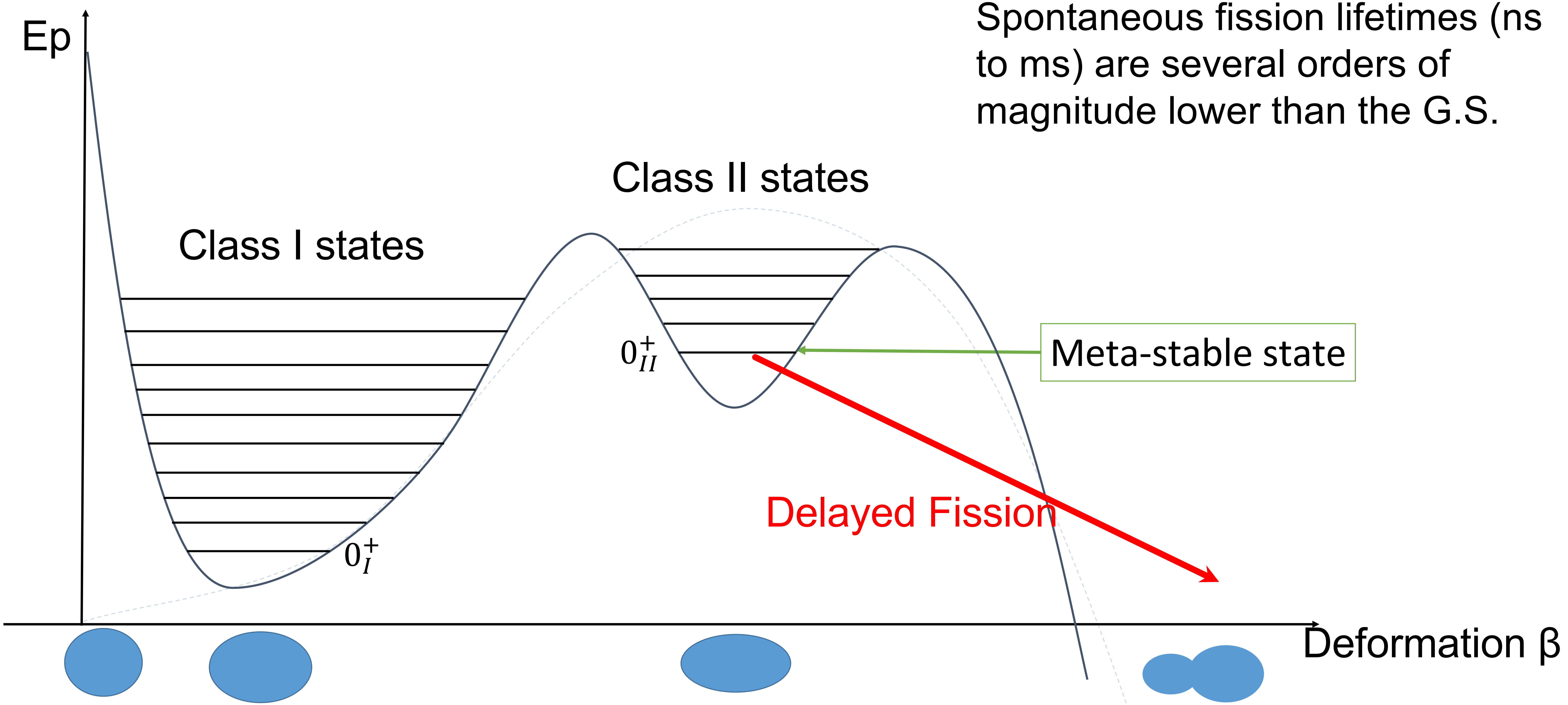
# Gamma decay of fission shape isomers – Corentin Hiver Ph.D thesis

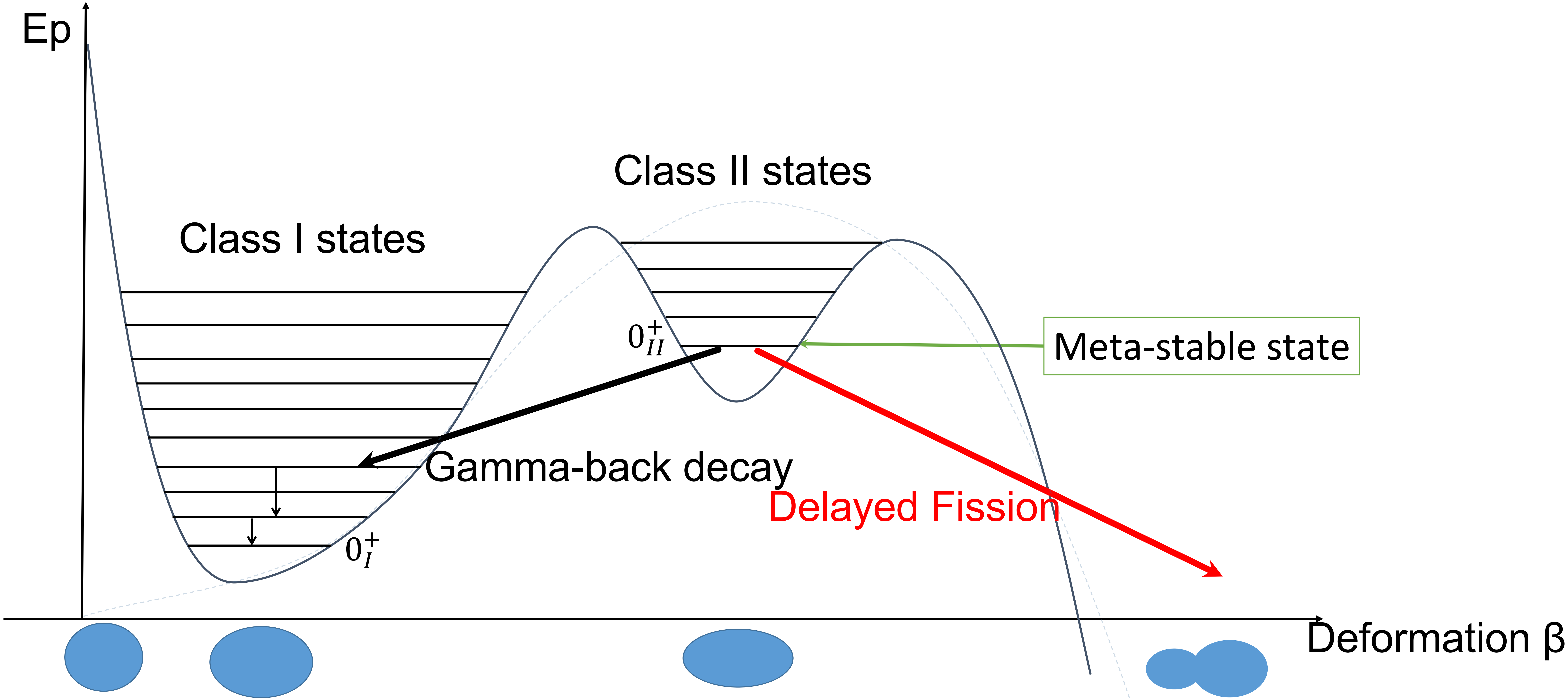


# Most isomers decay by delayed fission

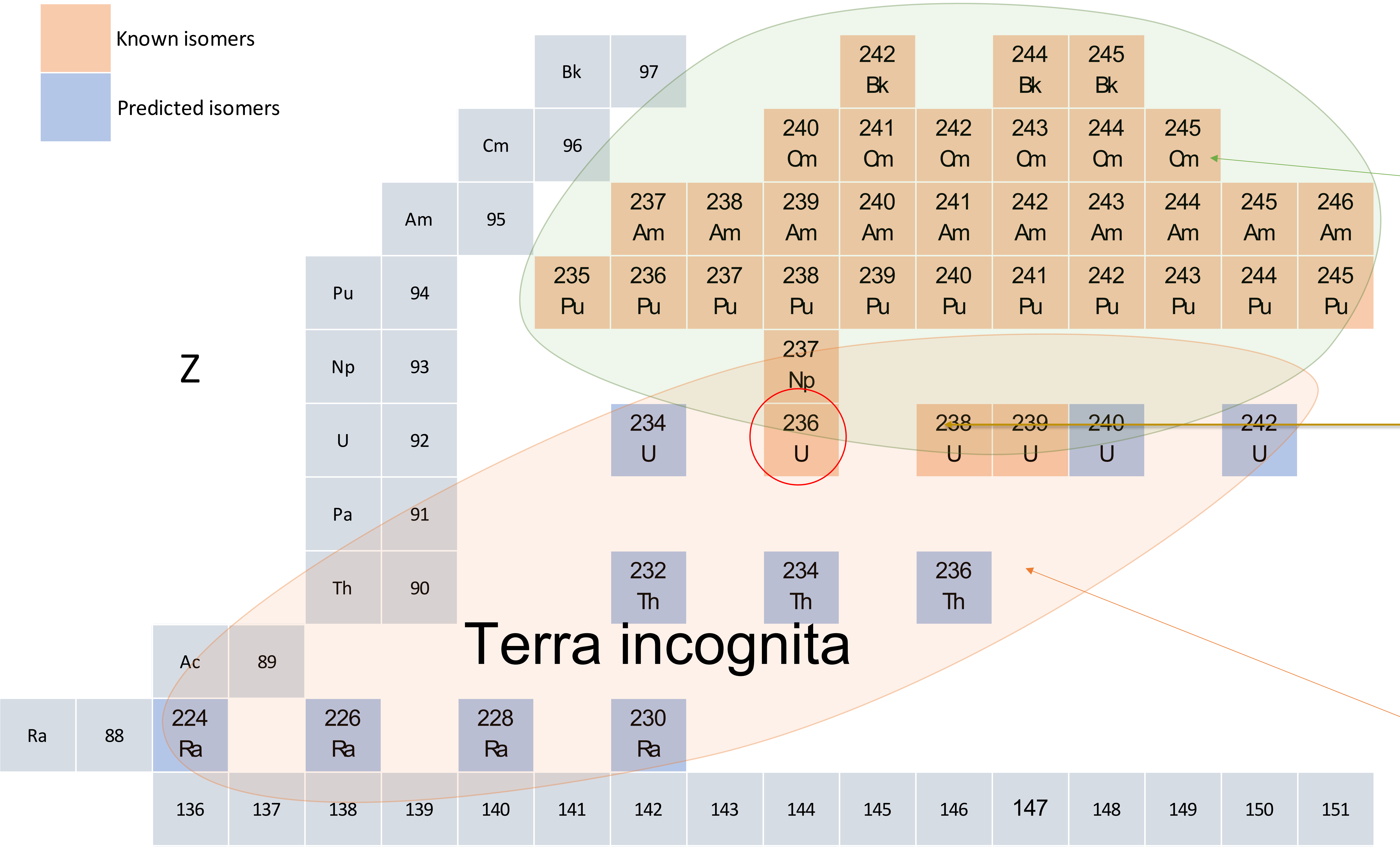
Spontaneous fission lifetimes (ns to ms) are several orders of magnitude lower than the G.S.

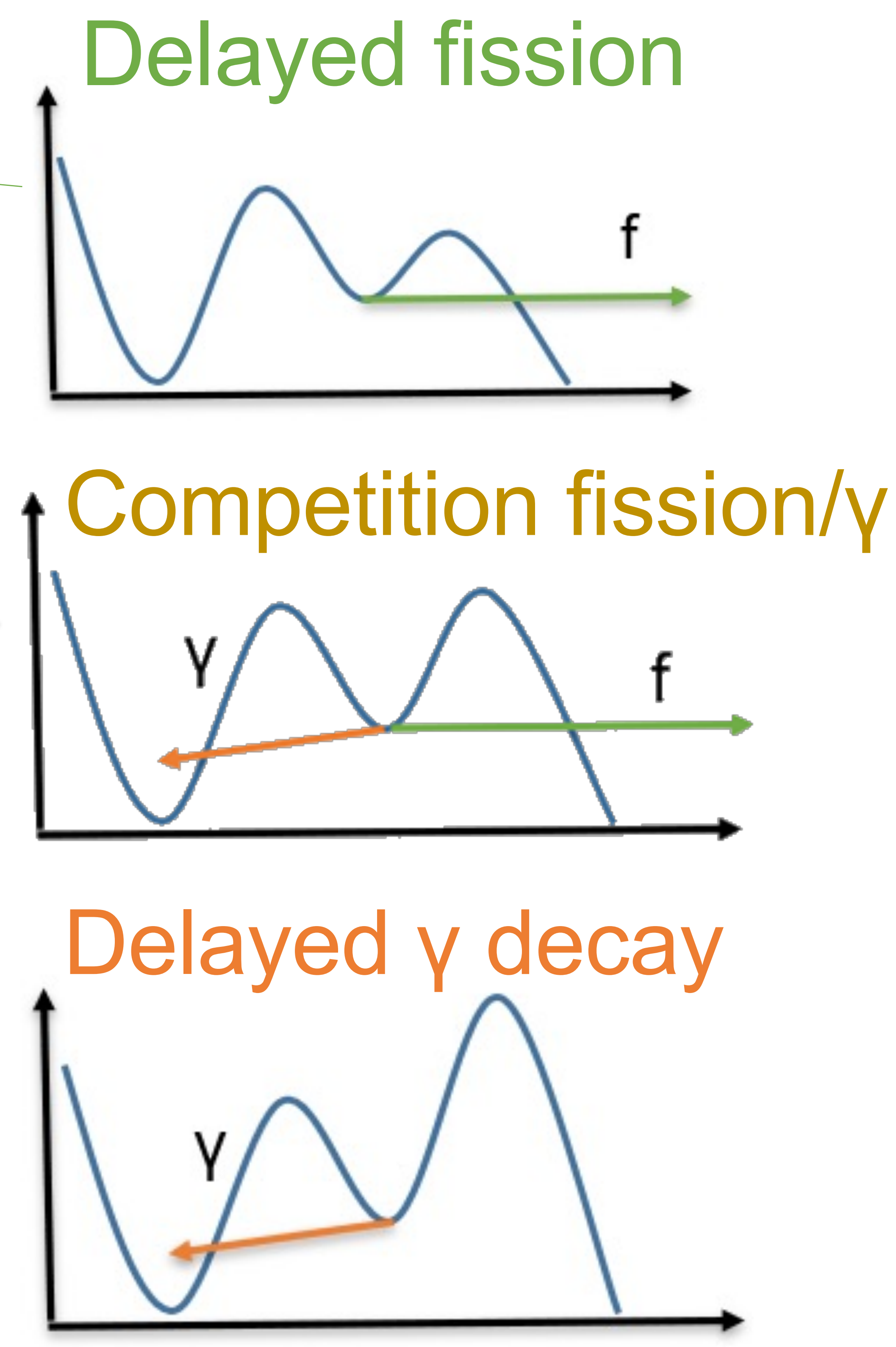


# Competing gamma back decay

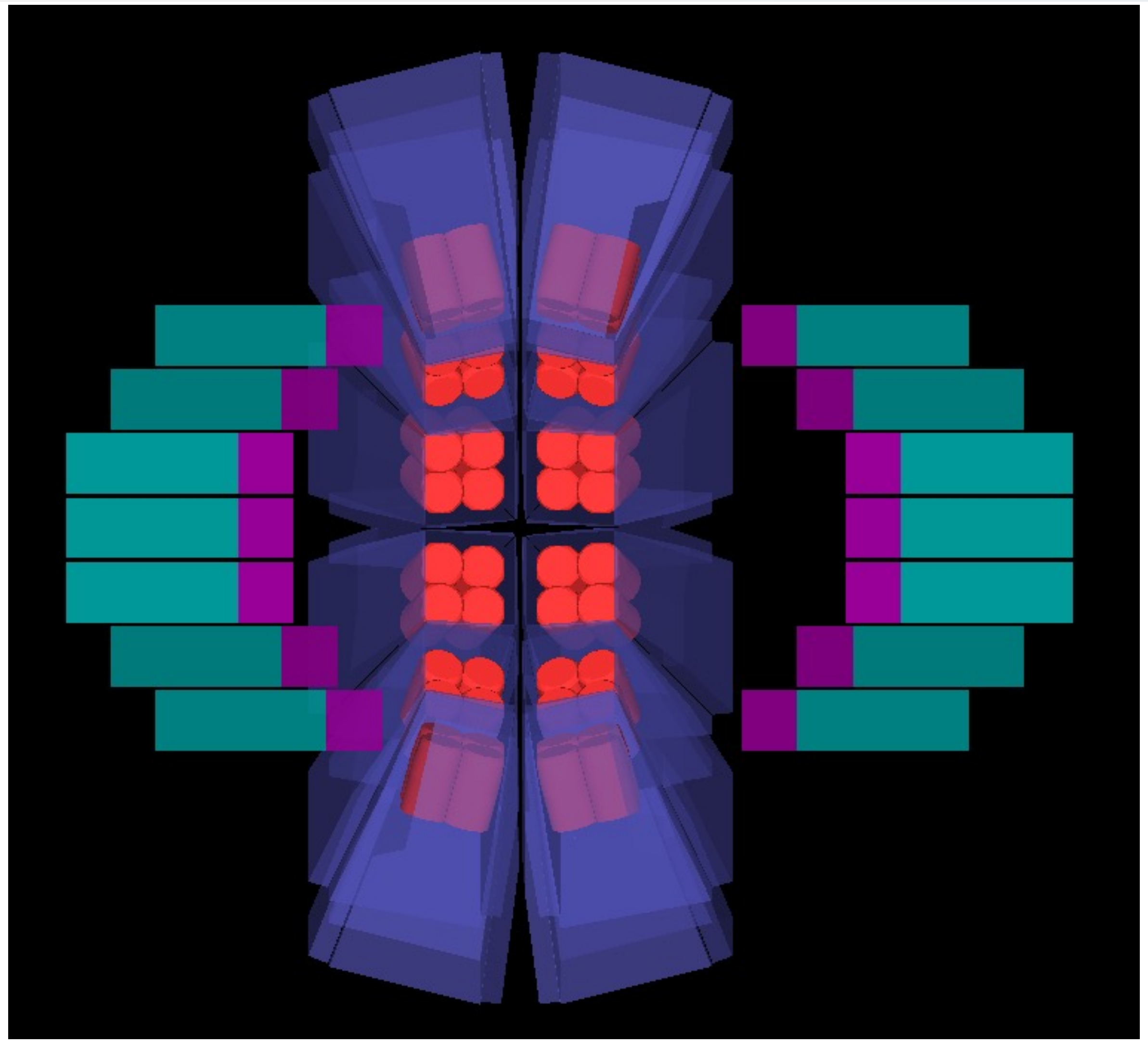


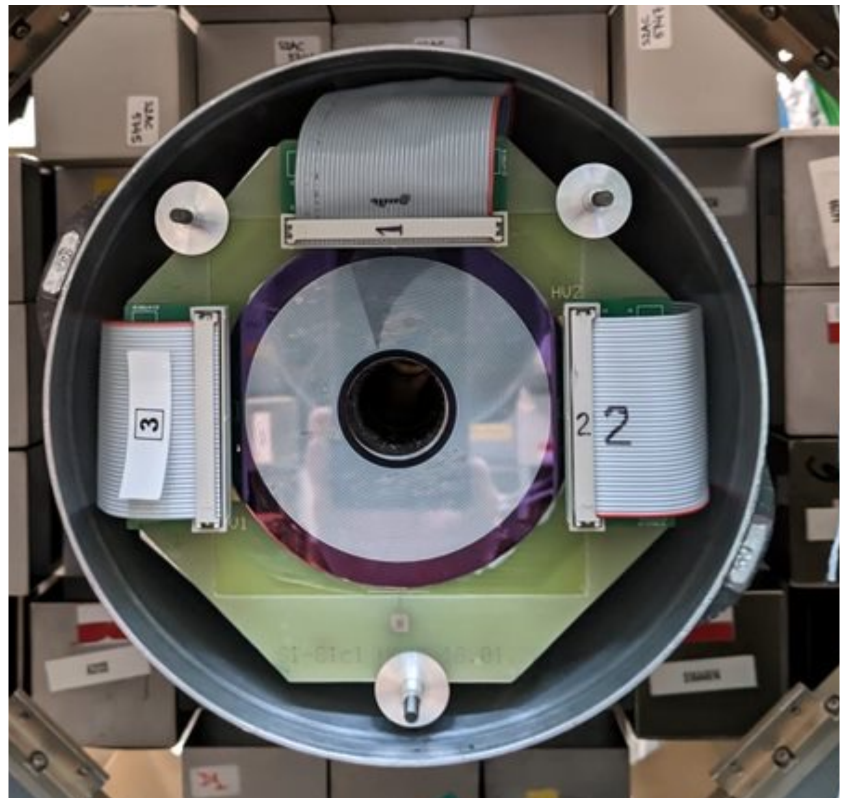
# Searching for gamma back decays



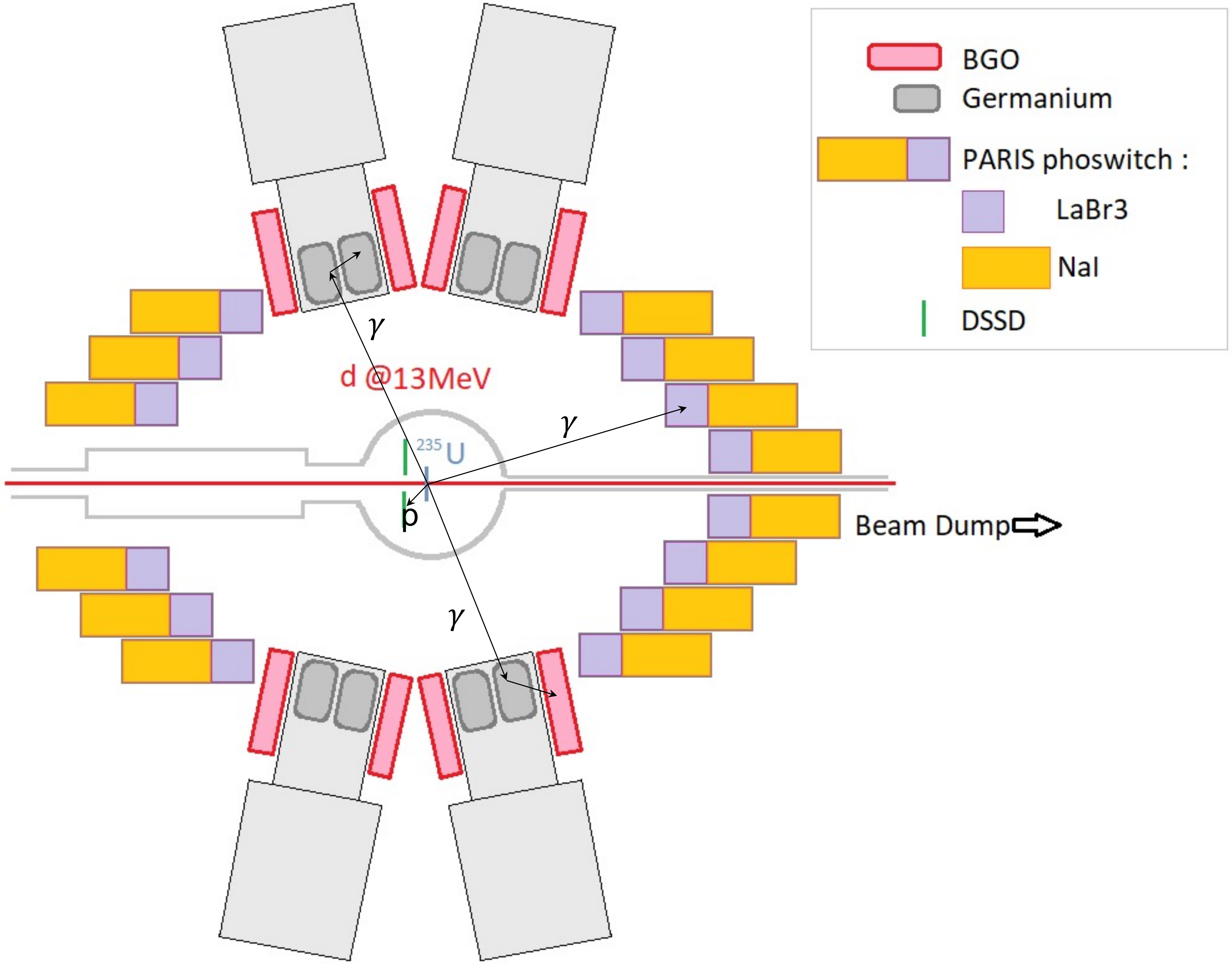



# Experimental setup: Data analysis ongoing



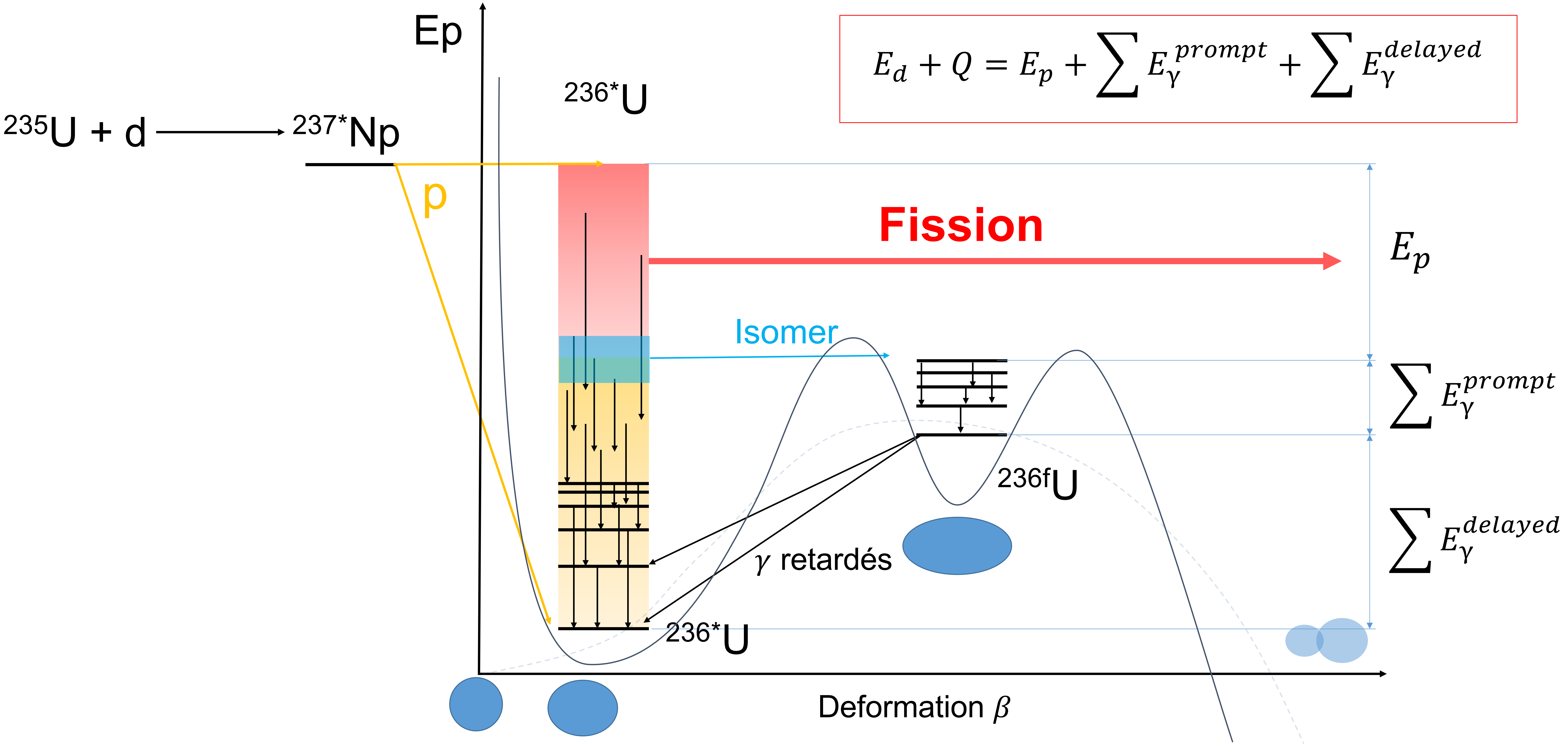


DSSD



# Selection of the rare back decay events through calorimetry

$$E_d + Q = E_p + \sum E_\gamma^{prompt} + \sum E_\gamma^{delayed}$$



# Experimental campaign: IJC Lab, Orsay

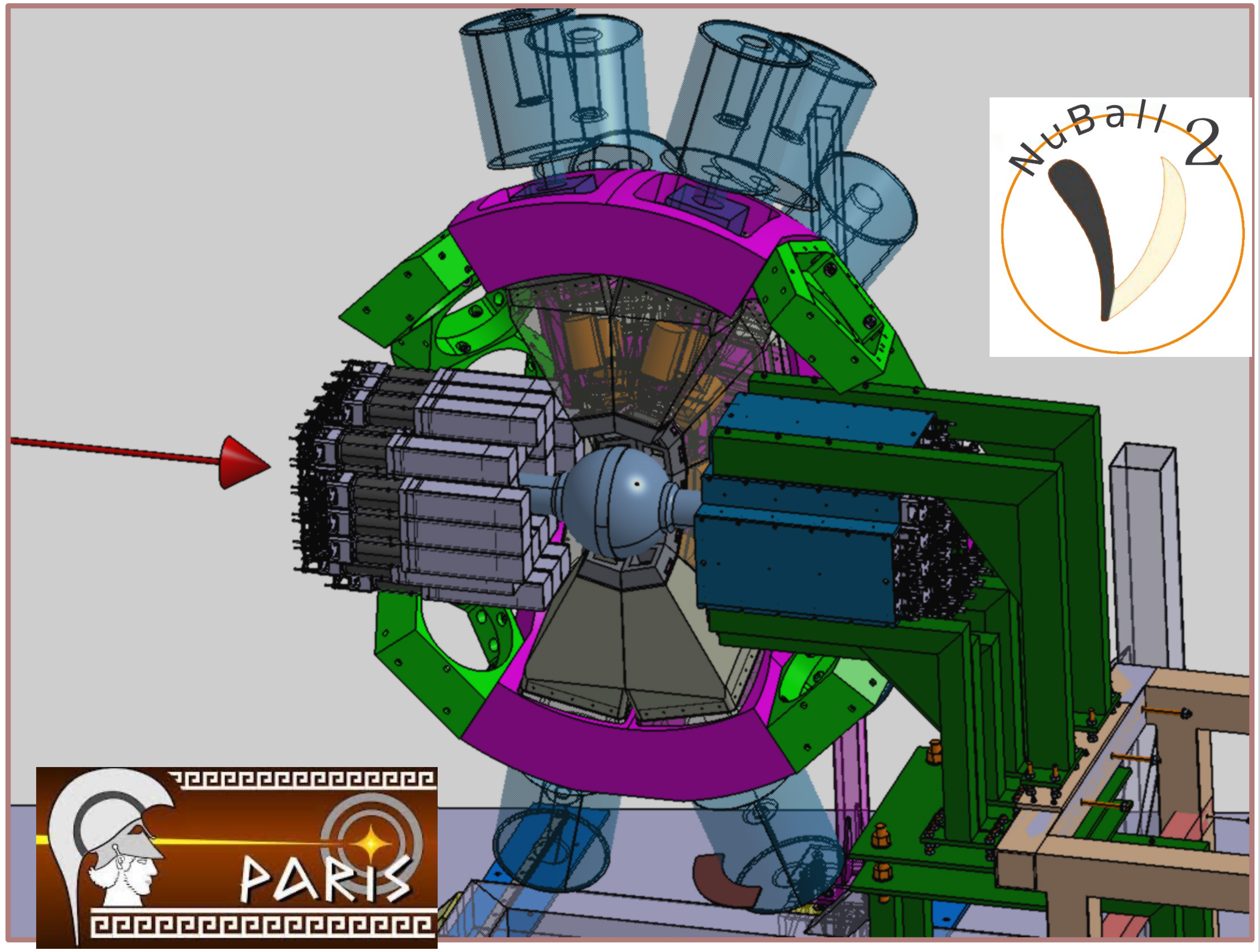
**Spring 2023**

✓ ***Search for the fission shape isomer in $^{232}$Th***
spokesperson and data analysis: C. Hiver

✓ ***$^{194,196}$Hg fission studies***
spokesperson and data analysis: K. Miernik

❑ ***Investigation of high spin structures in $^{44}$Ti and $^{42}$Ca via discrete and continuum gamma spectroscopy using nuBall2, PARIS and OPSA setup***
spokespersons: M. Matejska-Minda, K. Hadyńska-Klęk
data analysis: M. Matejska-Minda

✓ ***Emergence of collectivity near magic nuclei: Coulomb-excitation of $^{62}$Ni*    (* $^{60}$Ni)***
spokespersons: : K. Hadyńska-Klęk, M. Rocchini, N. Marchini
data analysis: K. Hadyńska-Klęk

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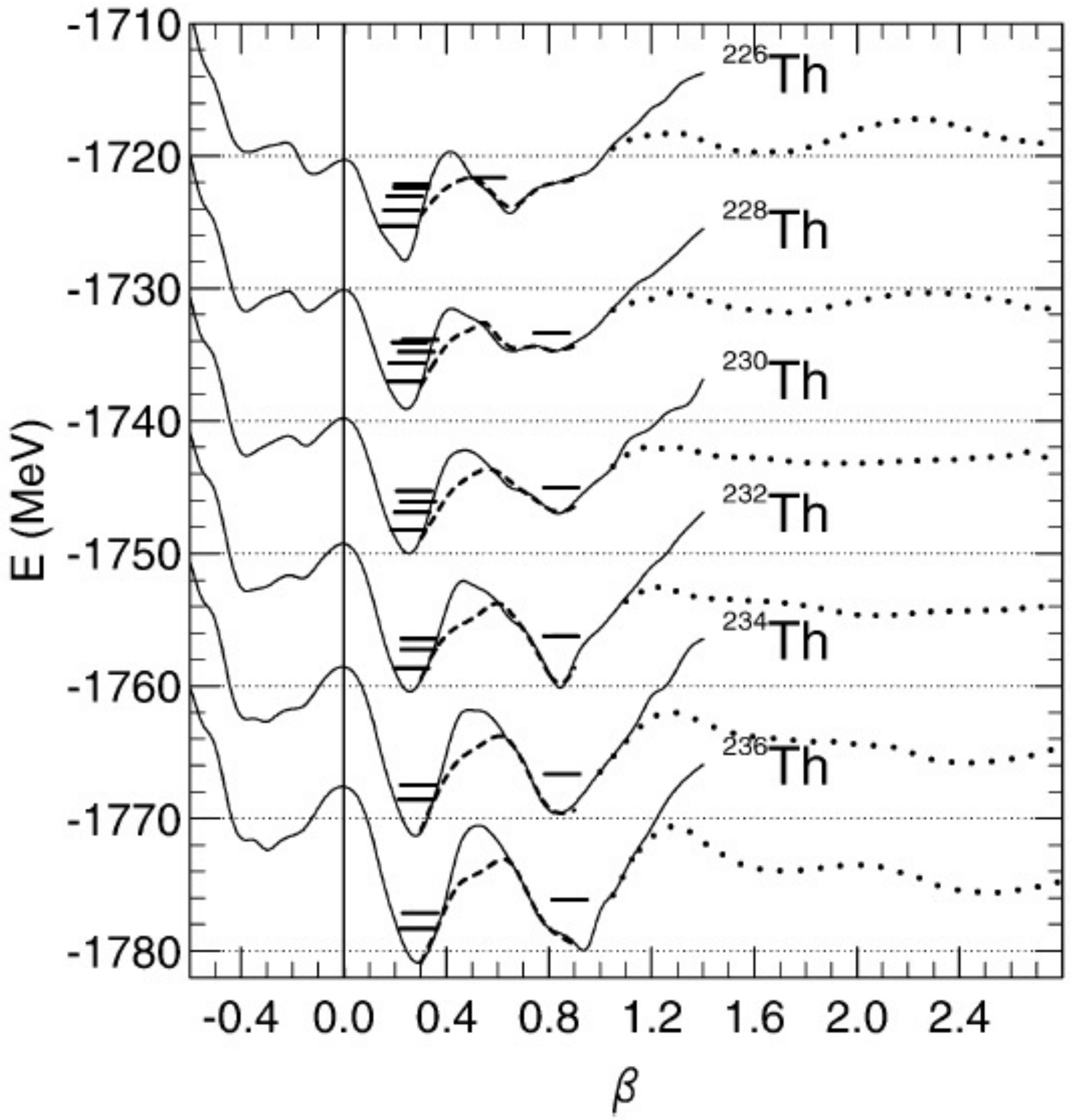
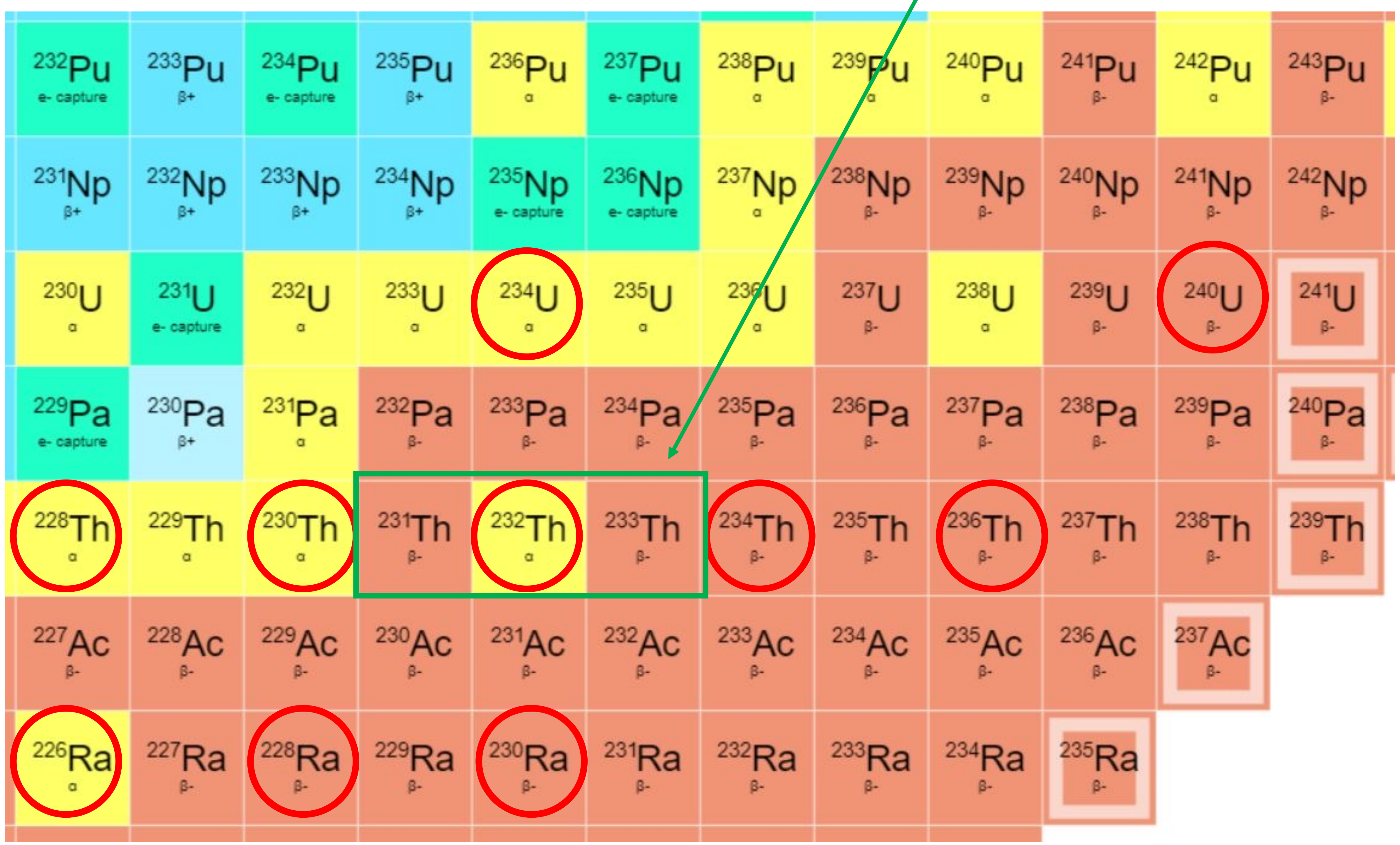
Accélérateur Linéaire et Tandem à Orsay

# Predicted fission shape isomers in the light actinides

S. J.-P. Delaroche, M. Girod, H. Goutte, J. Libert., Nuclear Physics A 771 103–168 (2006)
P. Jachimowicz, M. Kowal and J. Skalski, Phys. Rev. C 85, 034305 (2012)
B. Nerlo-Pomorska, K. Pomorski, J. Bartel, and C. Schmitt, Eur. Phys. J. A 53:67 (2017)

A second nu-ball2 experiment was performed in May 2023 to search for exclusive isomer gamma decay in $^{232,233}$Th



# Experimental campaign: IJC Lab, Orsay

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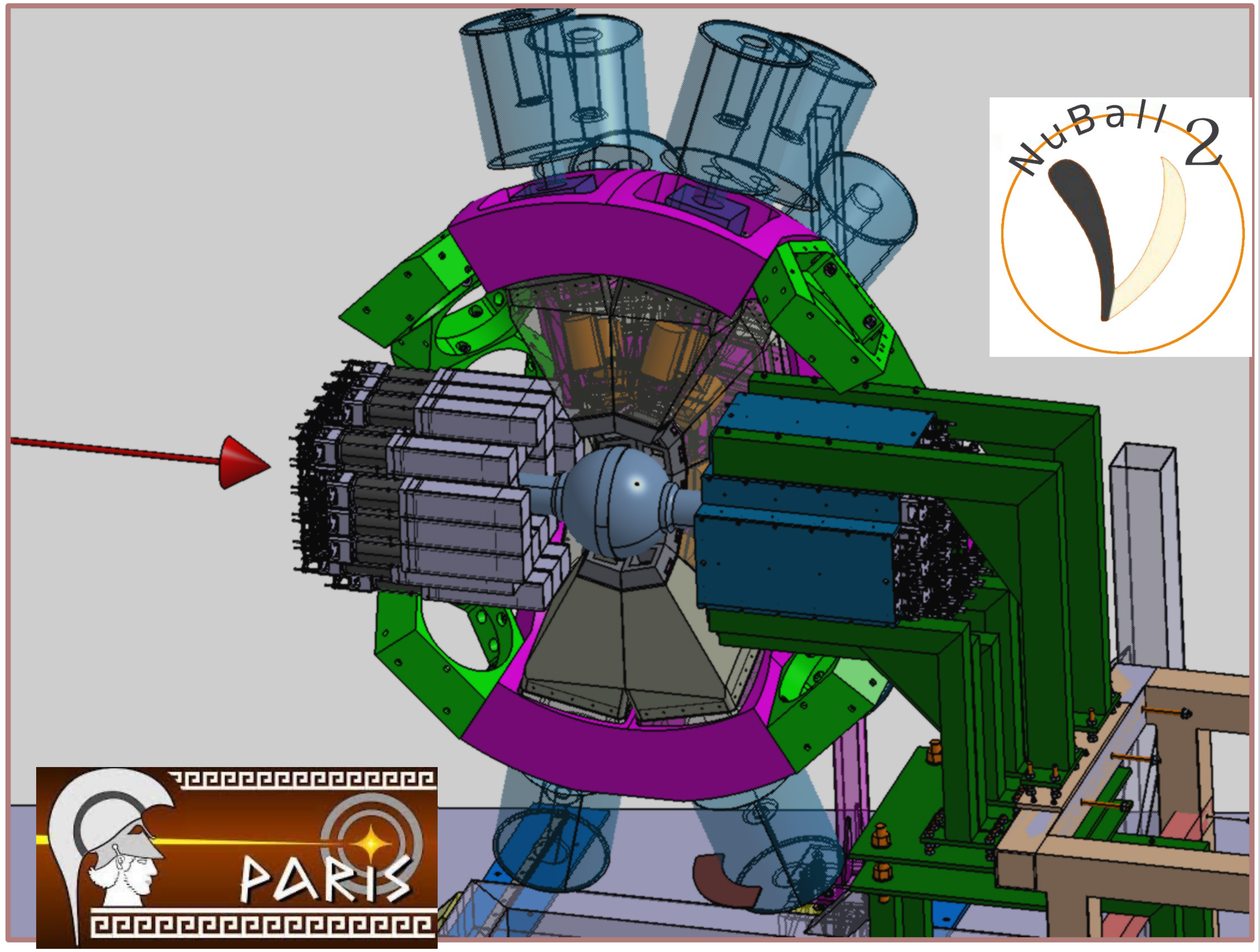

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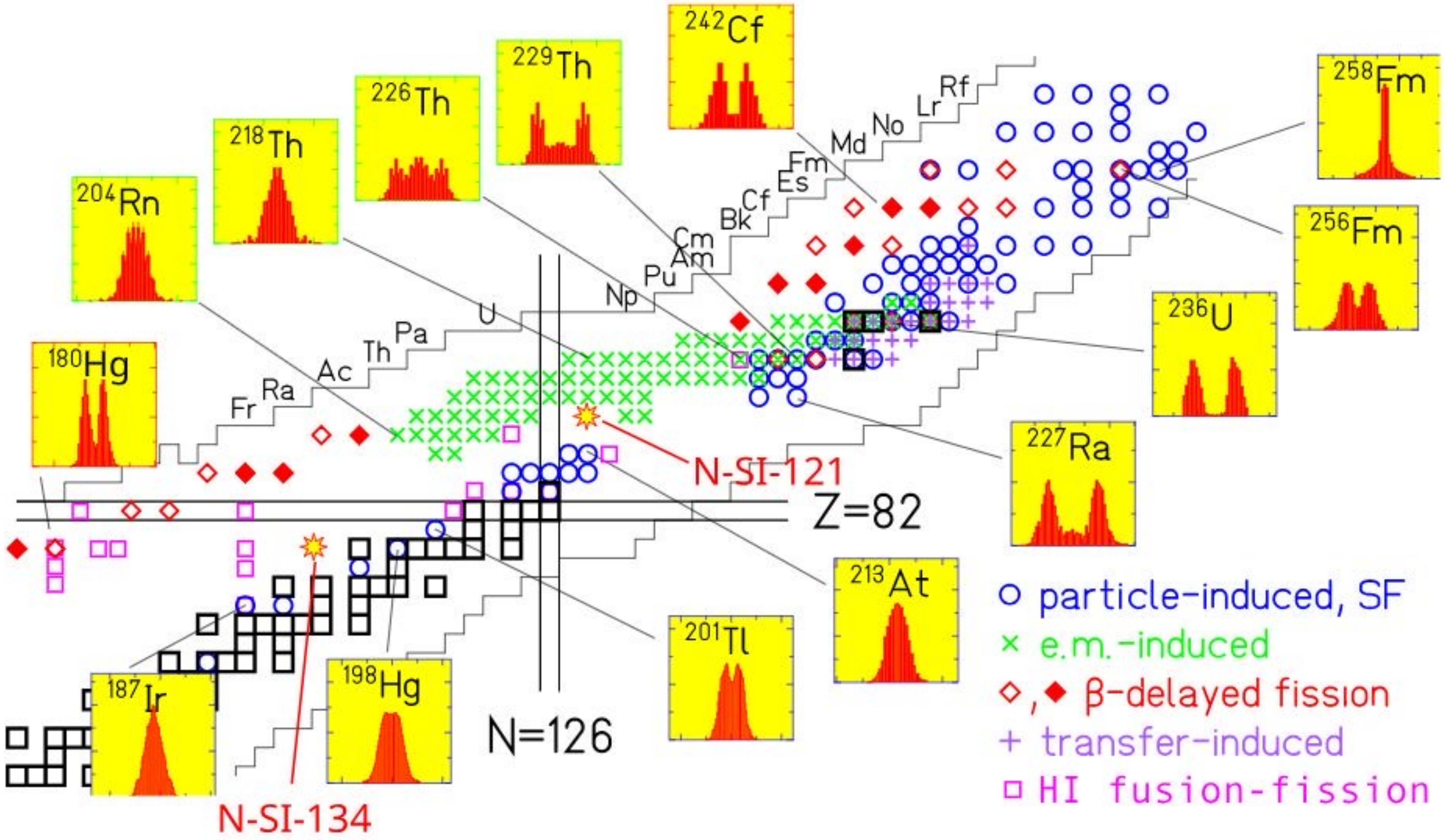
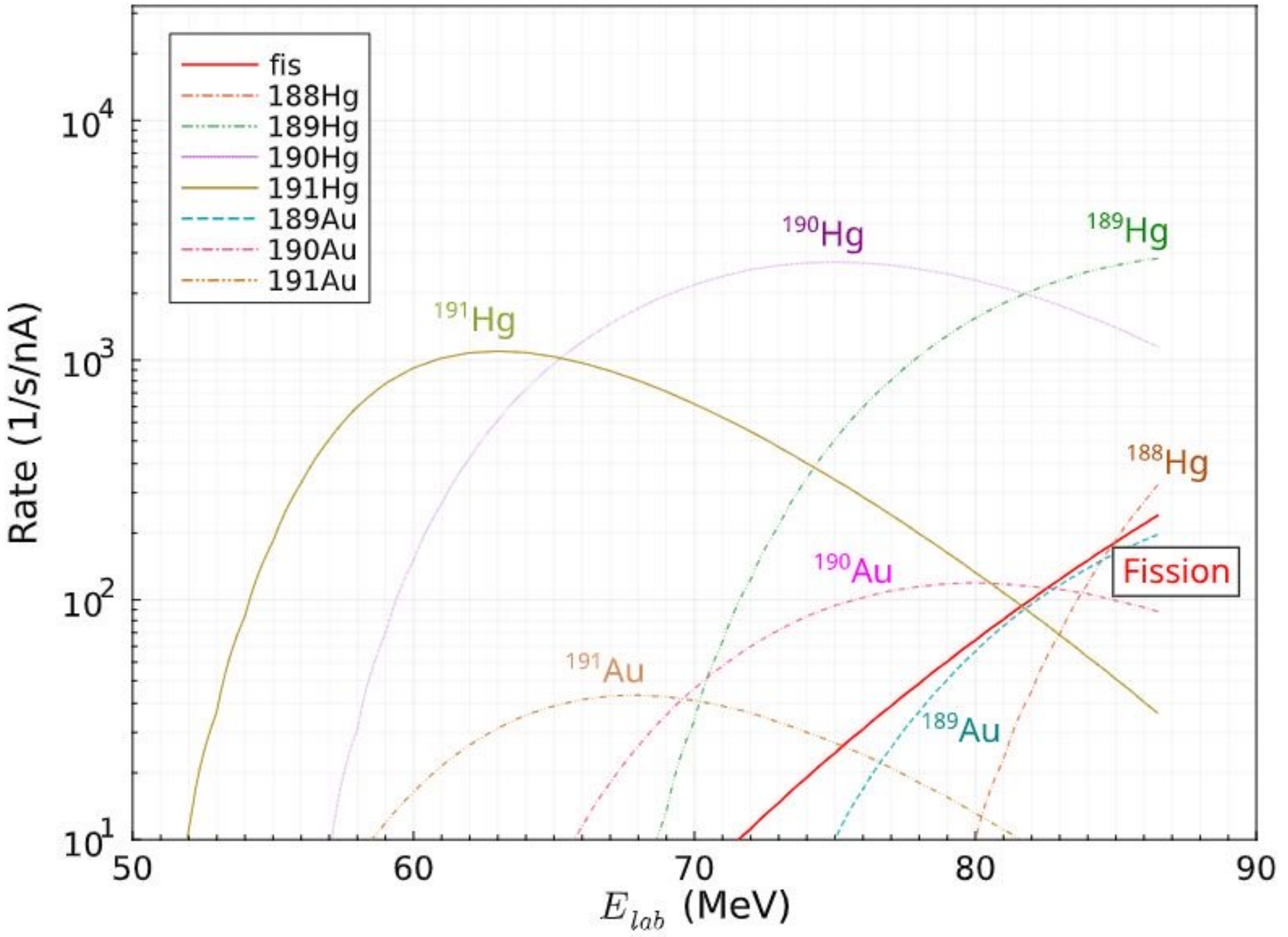
# Symmetric/Asymmetric fission transition




C. H Schimdt, B. Jurado Rep. Prog. Phys. 2018 (updated KM)

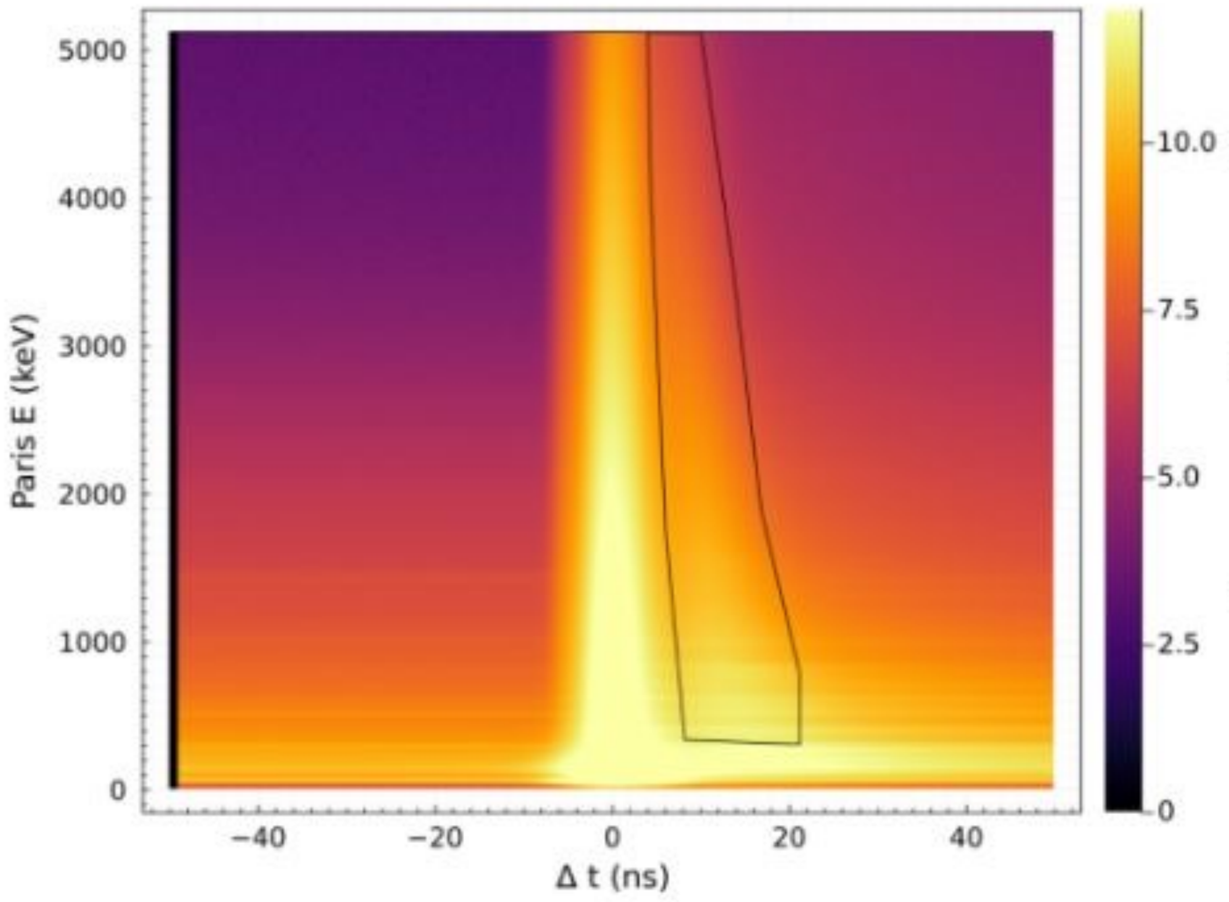
- Typical methods for fission fragments studies use TOF/ΔE detector or Z/A spectrometers
- Alternative method, based on $\gamma$-spectroscopy is possible with setups like $\nu$-ball.

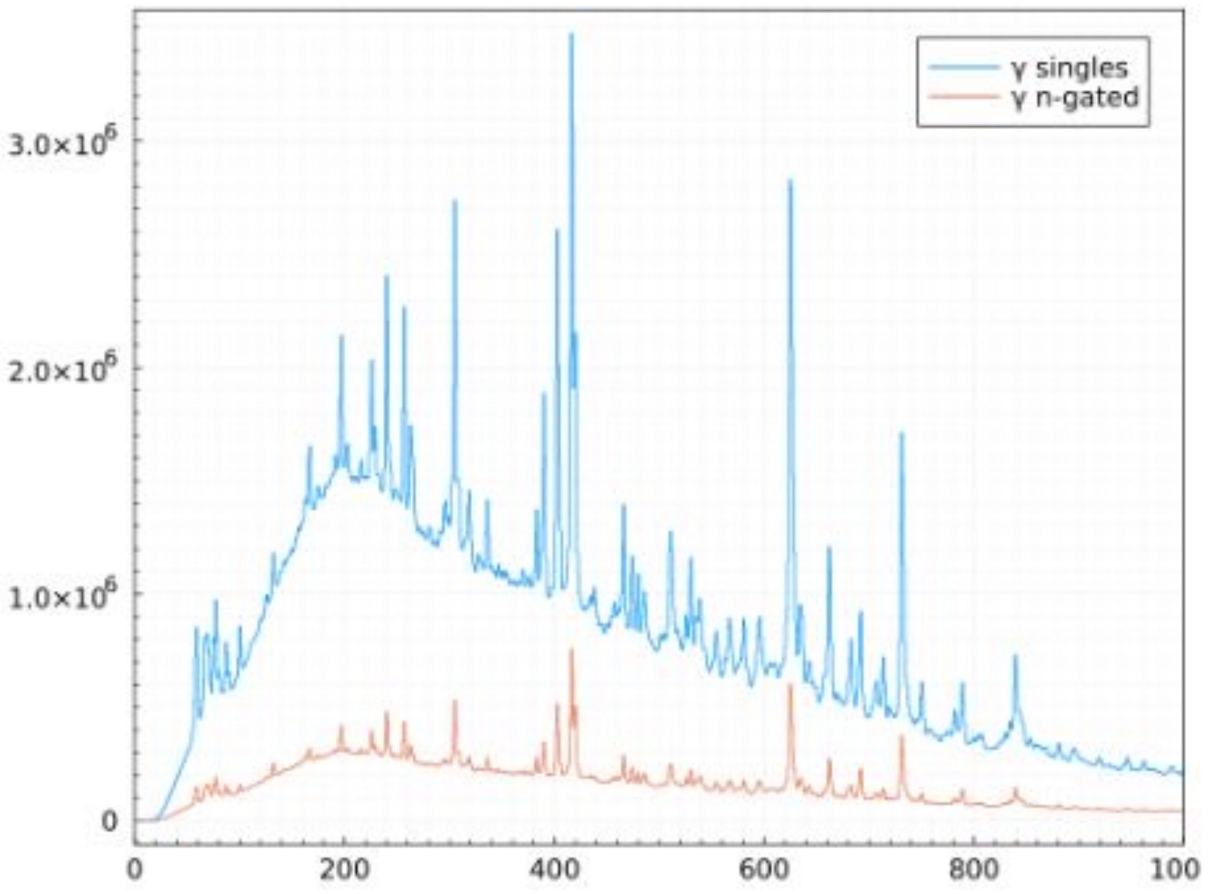
# 182W(12C, f) heavy-ion induced fission

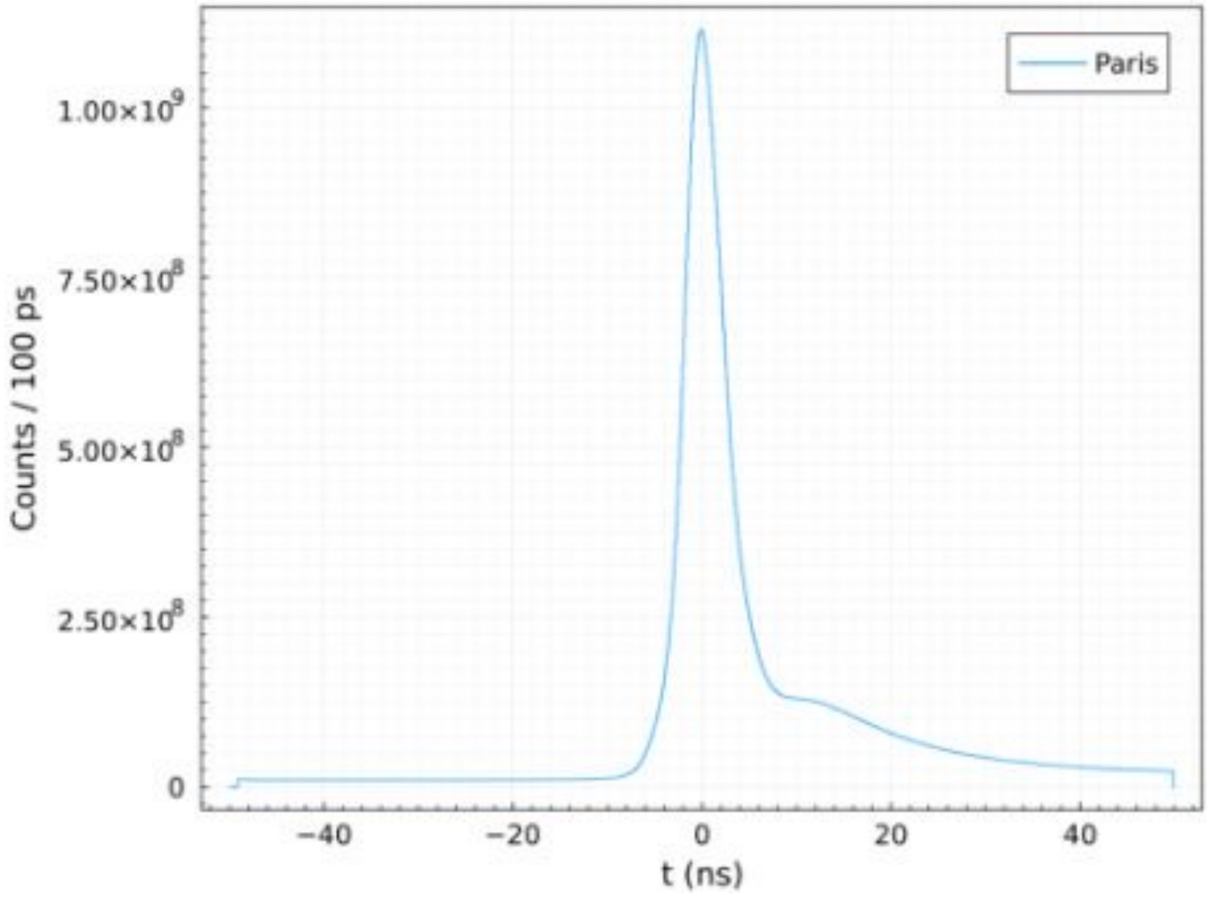



- Experiment: very stable beam of about 3 enA, limited by Clovers counting rate
- $E^* = 61.0 \pm 4.0$ MeV

# PARIS – neutron gate

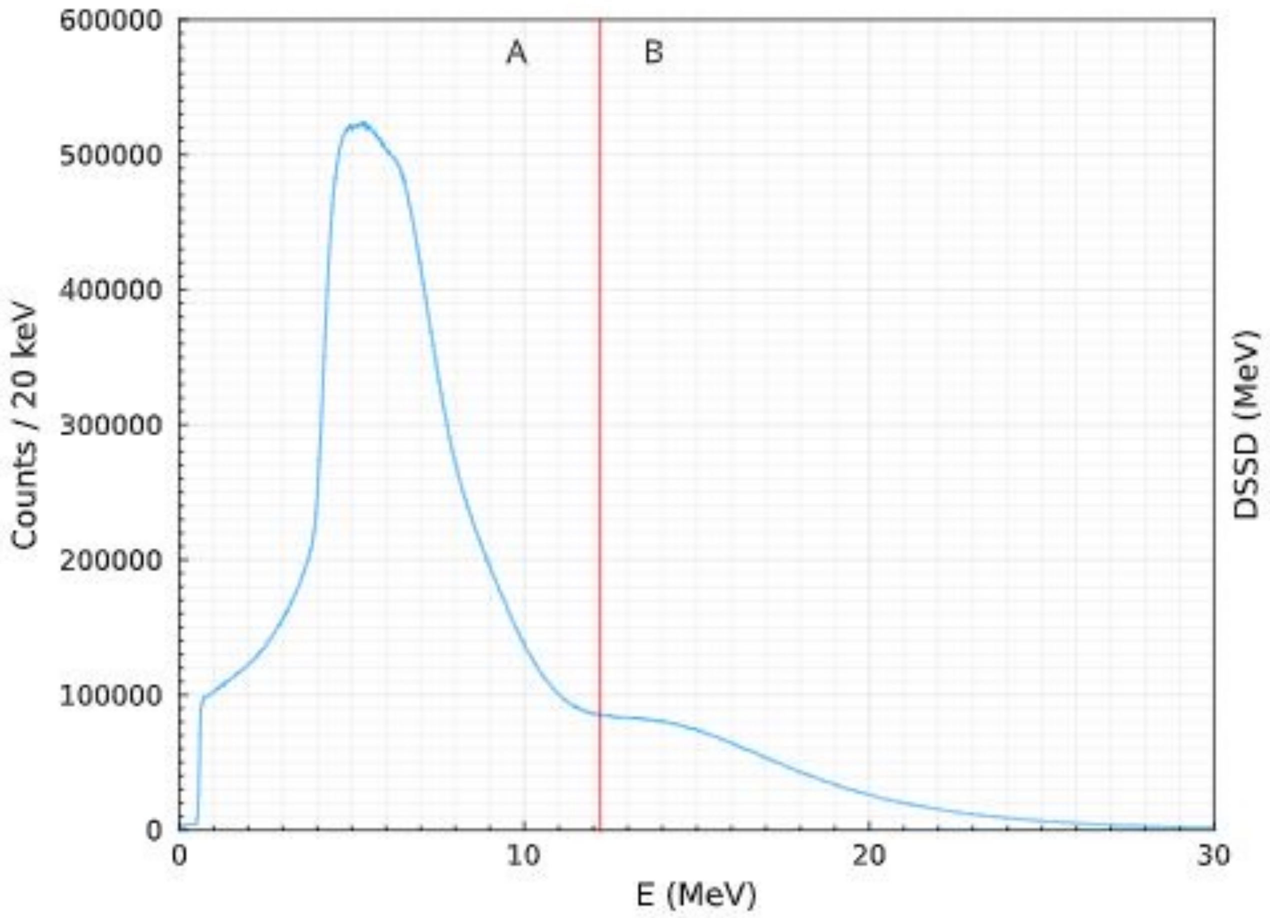


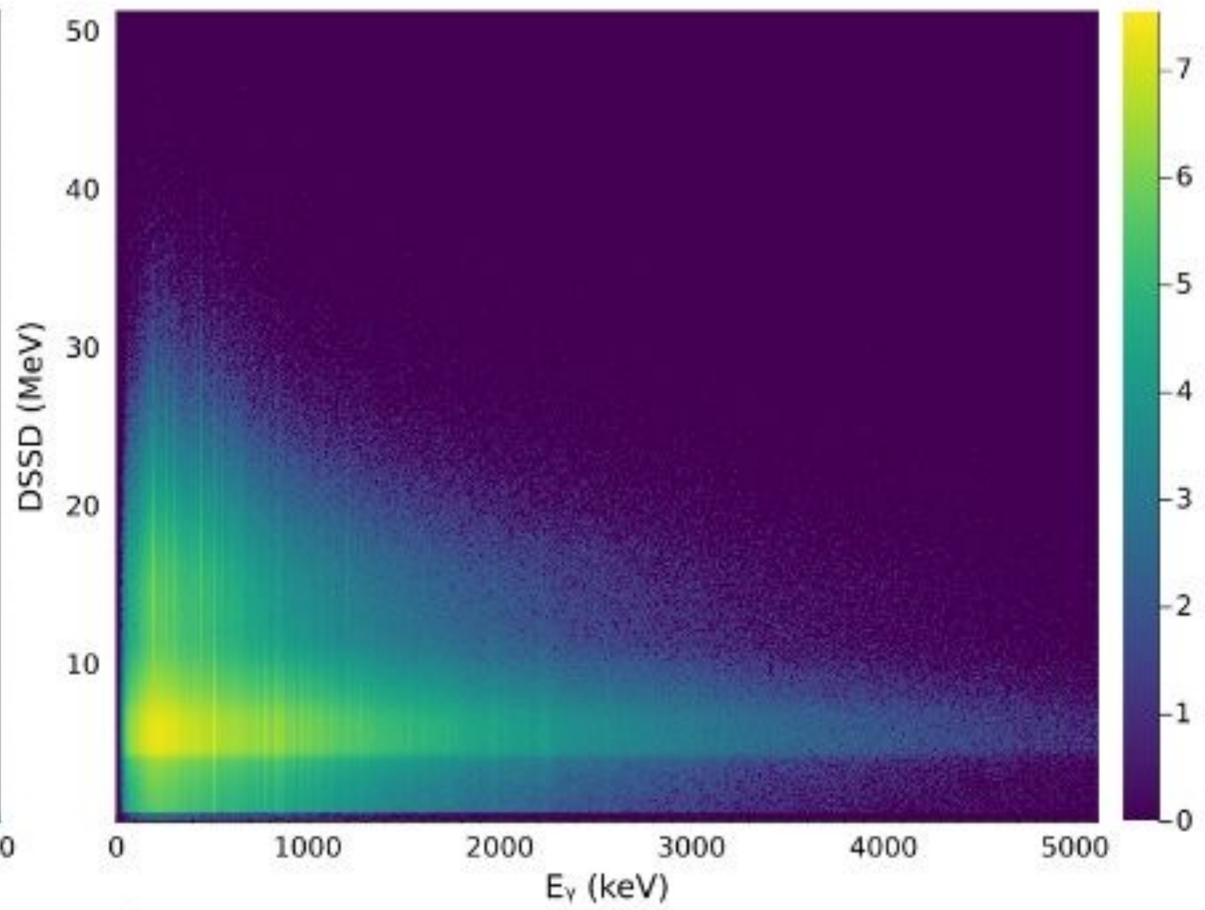



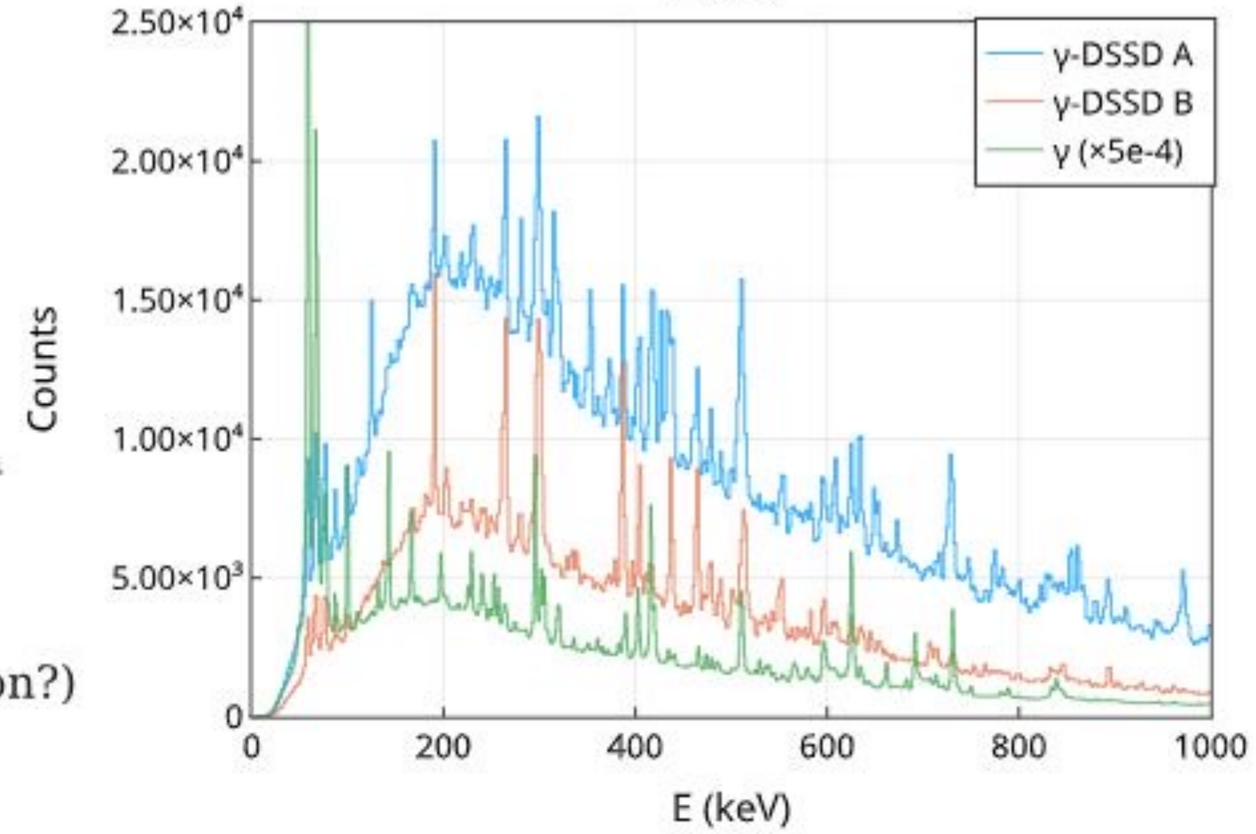

- "Neutron" gate on Paris E-t spectrum
- Gamma gated by neutron shows correct strong fusion-evaporation (3n, 4n) lines
- Usefulness in selection of fission events to be explored
- Gating on fission fragment lines to obtain neutron spectrum to be explored

# DSSD gates




- Two groups of events in DSSD spectrum
- Gamma spectrum gated by range A or B show different lines
- Gamma singles show yet different pattern
- Group B → incomplete fusion (α2n, α4n) $^{186,188}Pt$
- Group A → to be identified (p/d evaporation?)



# OUTLOOK: HIL Warsaw - ALTO

- Systematic studies of the shapes and deformations across the nuclear chart
- Spectroscopy of fission isomers and heavy-ion induced fission
- Many successful experiments – analyses ongoing
- Work in progress on future experiments at ALTO and HIL
- Collaboration meetings planned for the next year

# Collective properties of nuclei studied at ALTO and CCB with PARIS Demonstrator

Maria Kmiecik, IFJ PAN Kraków

Jonathan Wilson, IJCLab Orsay

COPIN-IN2P3 Workshop

20–8 November 2023, Warsaw

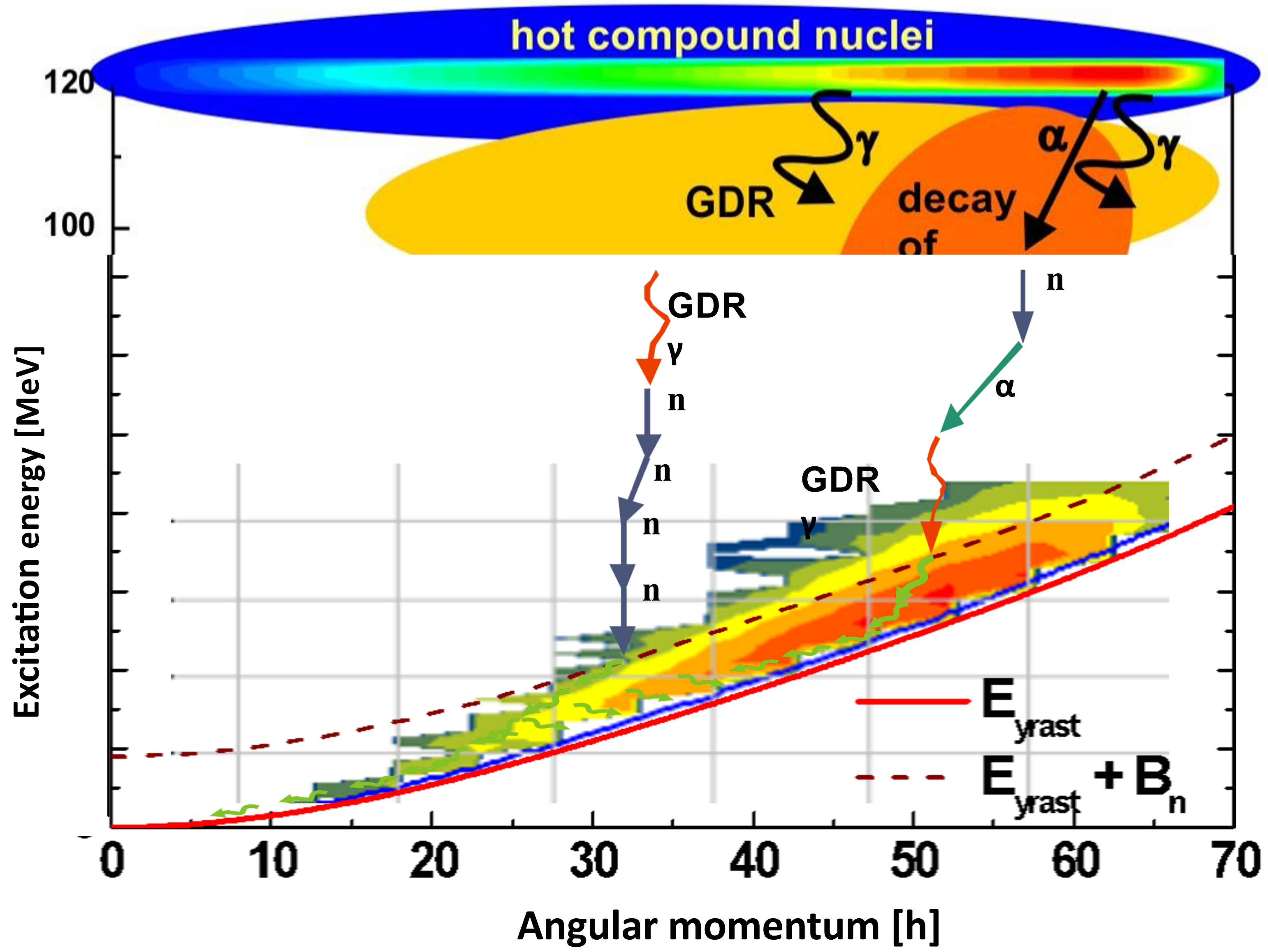
**COPIN: 06-126**

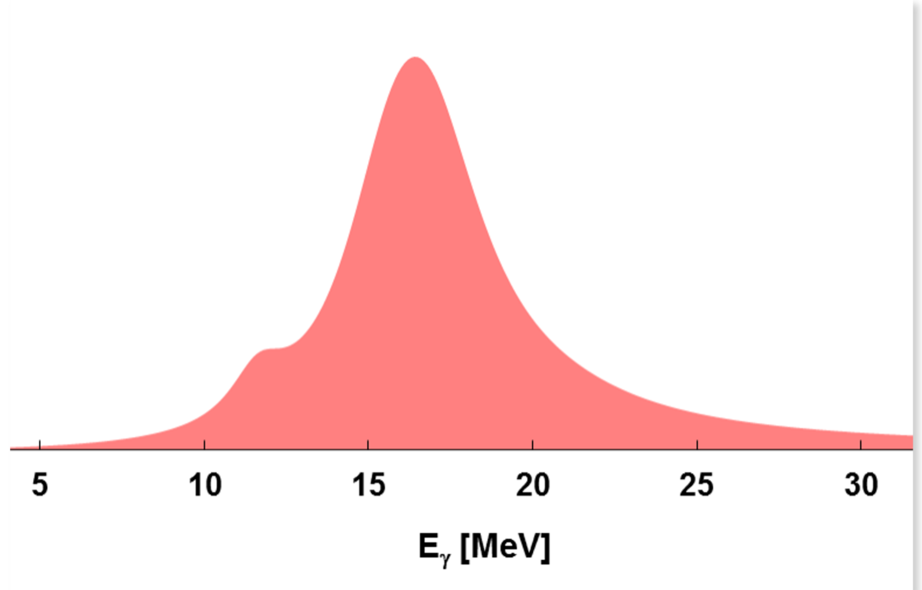
# Recent experiments performed (at ALTO,IJCLab)

- M. Ciemała (IFJ PAN Kraków) – Links between 80Sr compound nucleus' shape and its residue's deformation studied with the GDR using NuBall2+PARIS, experiment: Nov. 2022, data analysis: 2023;
- M. Matejska-Minda (IFJ PAN Kraków) – Investigation of high spin structures in $^{44}Ti$ and $^{42}Ca$ via discrete and continuum gamma spectroscopy using NuBall2, PARIS and OPSA setup, experiment: June 2023;

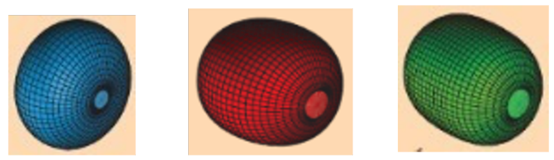
# Study of links between compound nucleus' shape and its residue's deformation

Link between deformation of hot compound nucleus and deformation of cold evaporation residue by the measurement of **GDR decay of compound nucleus**




- GDR high energy gamma rays
  - hot nucleus shape
- low energy transitions
  - deformation of excited residue



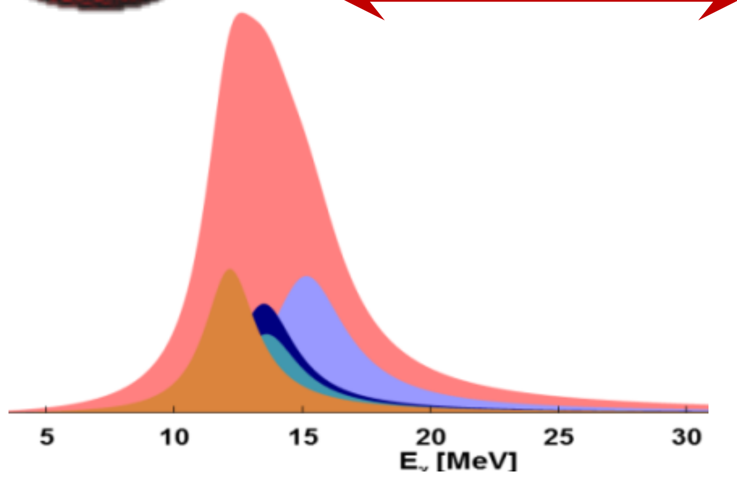
**Choosing the particular decay path**
**by coincidence measurement of high and low-energy γ rays**

# The idea

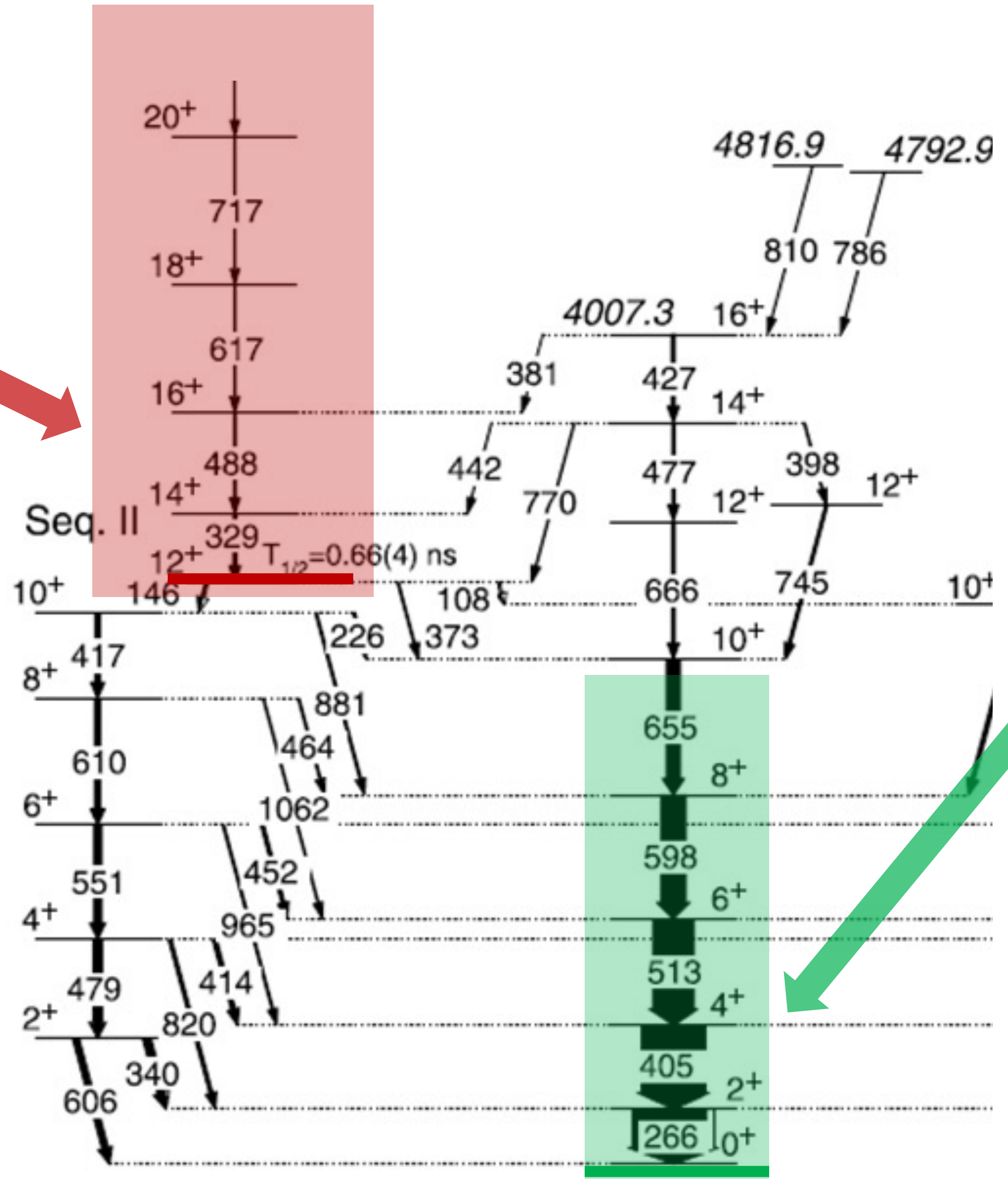
High-energy γ rays from $^{192}Pt^*$ CN decay in 4n channel
in coincidence with low-energy transitions in $^{188}Pt$

How the deformation changes along the decay path?

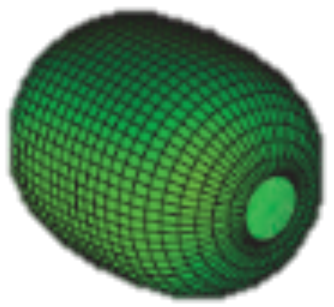
**β=0.16 and γ=−40°**
**triaxial**




Gate on transitions

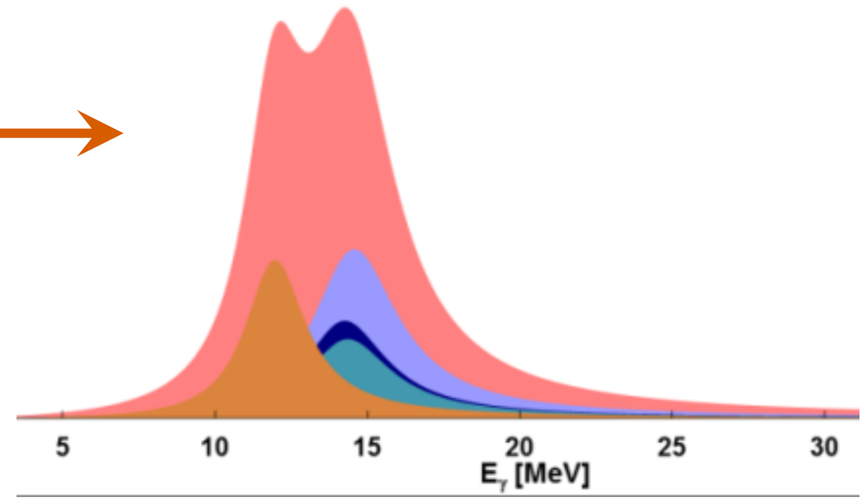



S. Mukhopadhyay et al., Phys. Lett. B 739, 462 (2014)



**β =0.18and γ=−6°**
**near prolate**

GDR strength functions for CN decaying to particular states of $^{188}Pt$

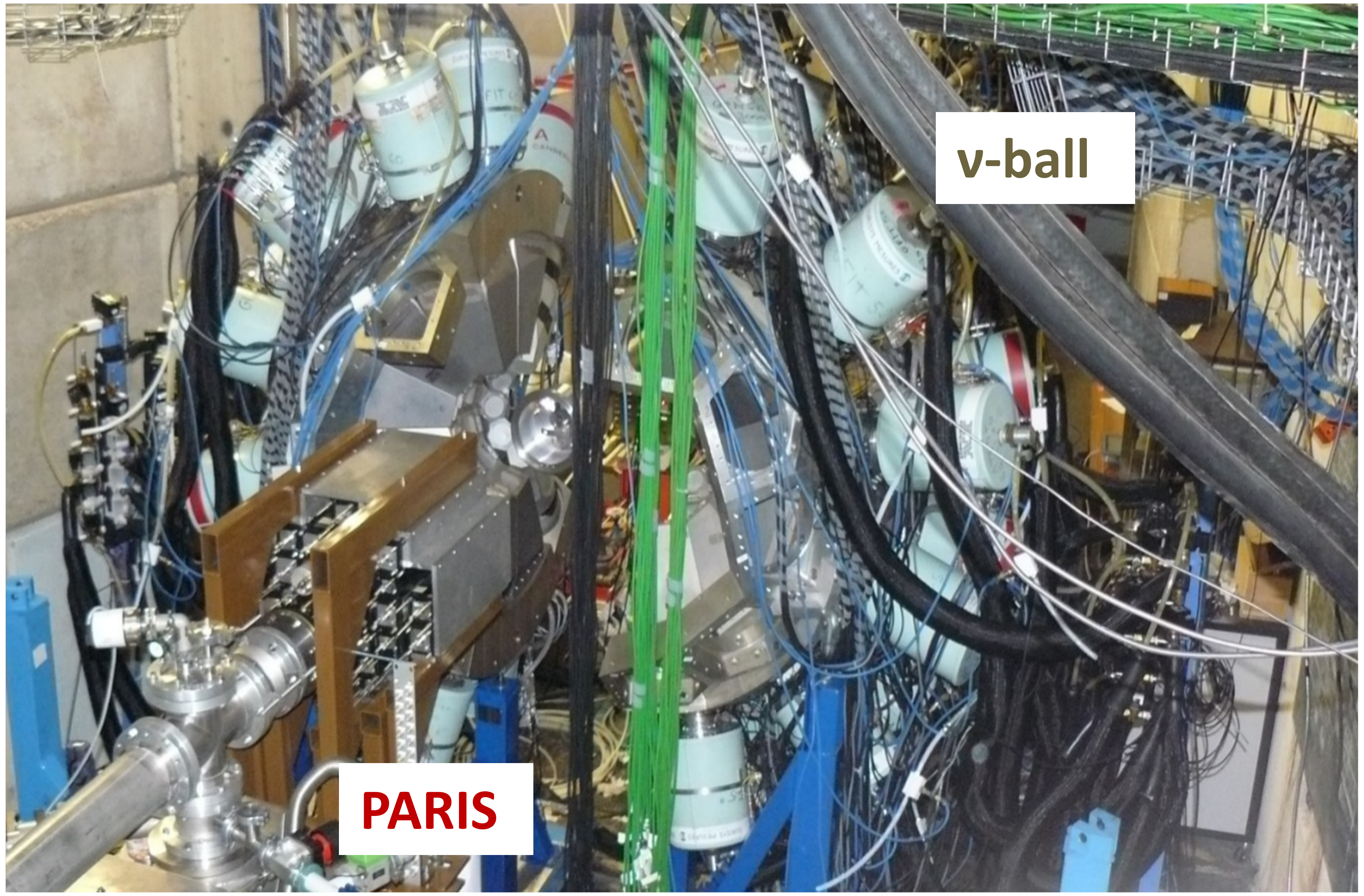


# The nuBall + PARIS experiment at IPN / IJCLab

**ν-ball array**: 33 Clovers +10 Coaxial HPGe coupled to 33 **PARIS** detectors:

11 $CeBr_3$:NaI phoswiches,
22 $LaBr_3$:NaI phoswiches.

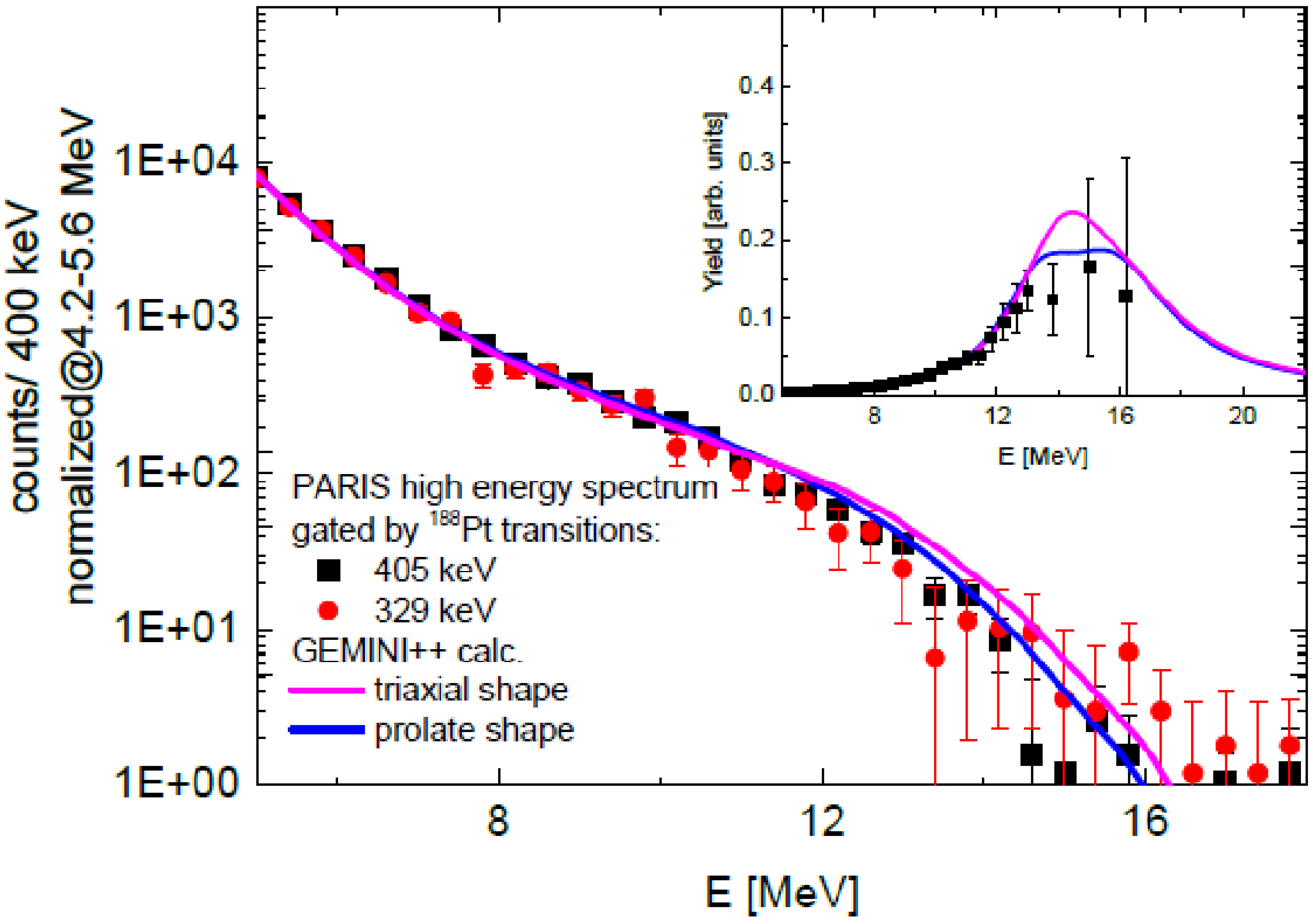
Triggerless DAQ by FASTER digitizer




## $^{18}O + ^{174}Yb \rightarrow ^{192}Pt$

- Beam energy: 90 MeV
- E* = 59 MeV
- T = 1.5 MeV
- $L_{max}$ = 38 ħ
- Target thickness: 1.5 mg/cm$^2$
- AmBe+Ni used for high energy callibration (up to 9 MeV)

# Analysis – Comparison to statistical model




Better agreement to experimental data is seen for the calculations assuming prolate-like shape of the nucleus.

Suggestion that either:
the assignment of the triaxial deformation for 12+ isomer is wrong
or
the nucleus does not preserve the shape during the decay.

*M. Ciemała et al., Acta Phys. Pol B Proc. Suppl. 16, 4-A3 (2023)*

# Links between $^{80}$Sr compound nucleus' shape and its residue's deformation studied with the GDR using NuBall2+PARIS

**Experiment N-SI-122: - IJCLab**

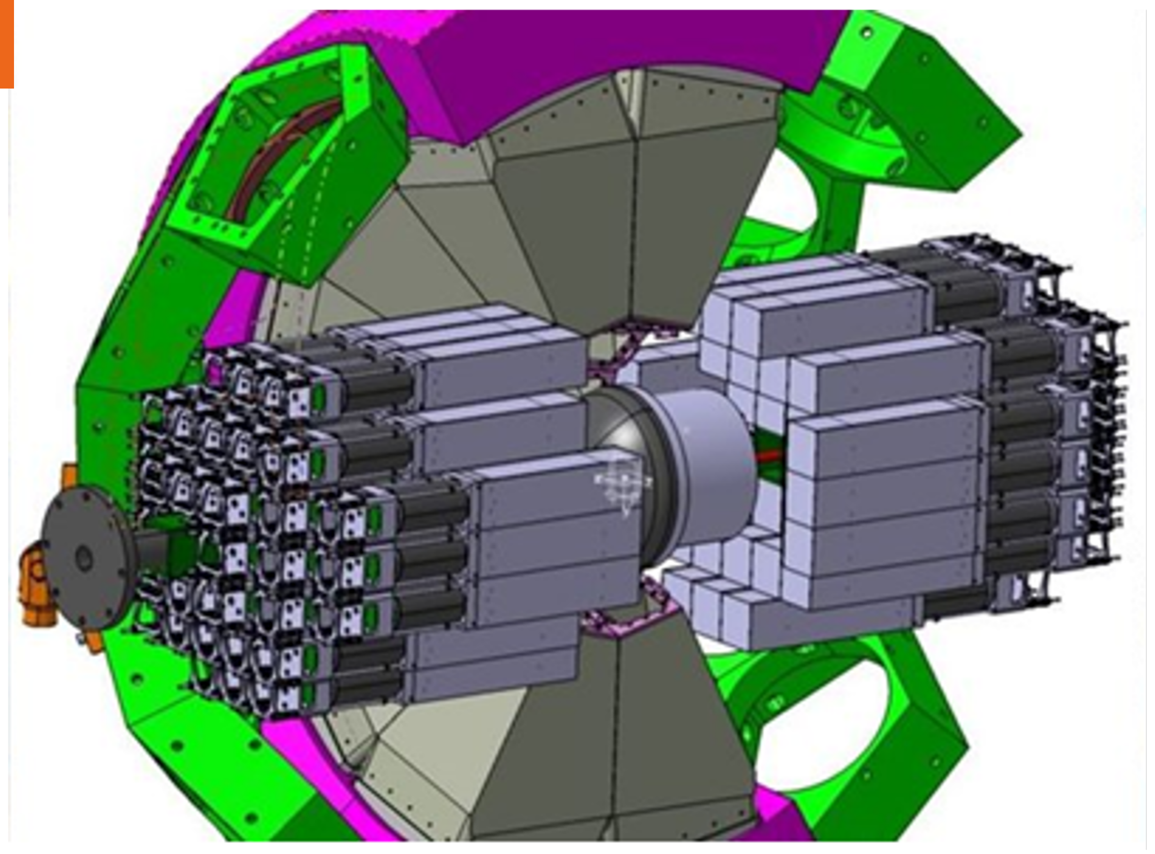
**Performed Nov 2022**

Spokesperson: M. Ciemała

**Study:**

- links between deformation of hot compound nucleus $^{80}$Sr and different deformation of the final state of the $^{76}$Kr residues;
- population of states of different deformation fed by high-energy γ–rays from GDR decay.

**By measurement** of high-energy gamma rays from the GDR decay in hot **$^{80}$Sr** compound nucleus by **PARIS array** (in wall geometry) in coincidence with discrete gamma transitions in **$^{76}$Kr** evaporation residue by **nu-Ball2 array.**



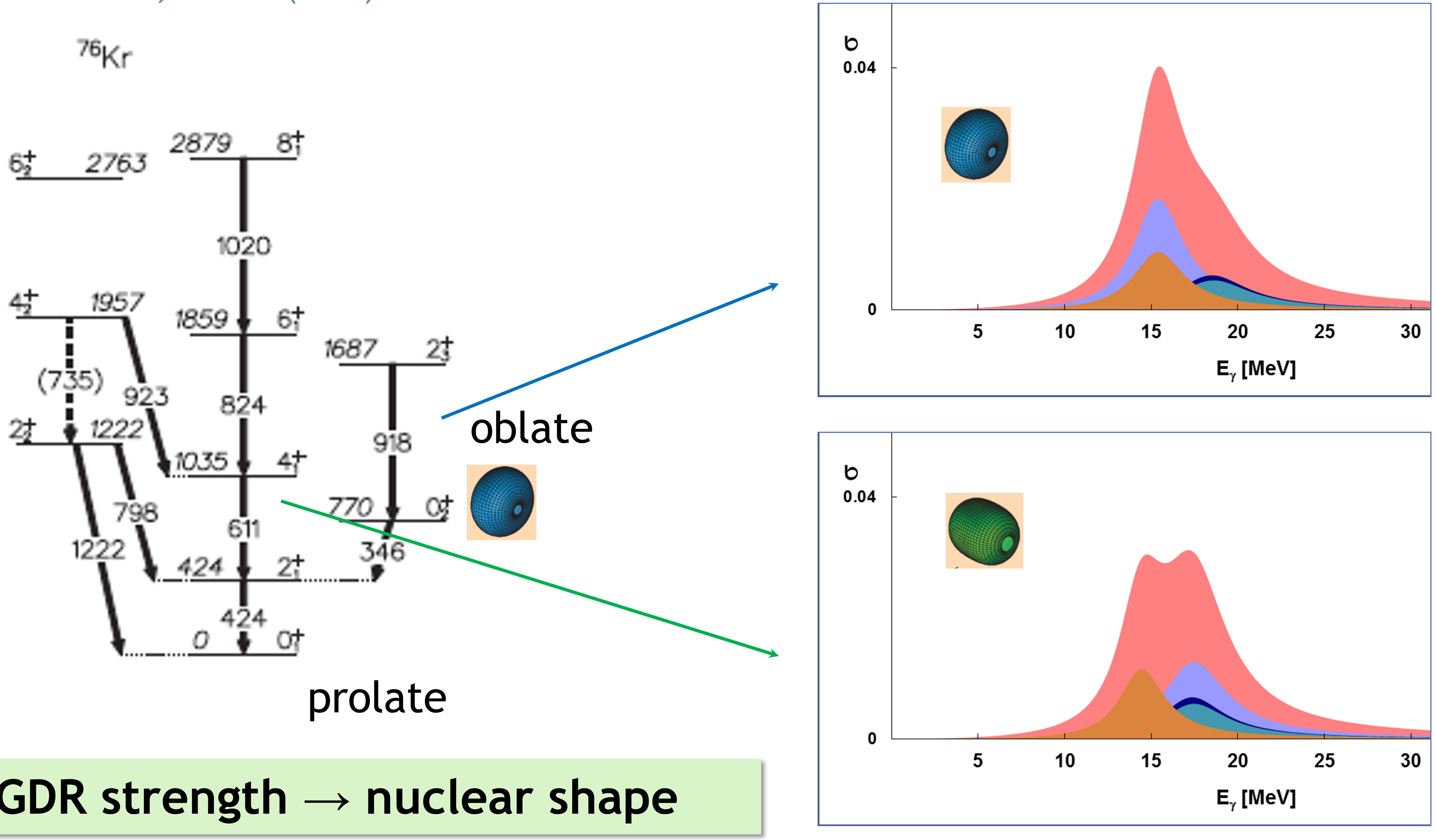
PARIS@NuBall2

# Method

High-energy gamma rays from the GDR decay in hot $^{80}$Sr compound nucleus measured in coincidence with discrete gamma transitions in $^{76}$Kr evaporation residue

GDR line-shapes

E. Clement et al., Phys. Rev. C 75, 054313 (2007)




**result: GDR strength → nuclear shape**

# The PARIS + NuBall2 experiment

**Reaction: $^{16}O$ @ 95 MeV on $^{64}Zn \rightarrow {}^{80}Sr^{*} \rightarrow {}^{76}Kr$**

Target: 1 mg/cm$^2$; pulsed beam,

Setup:

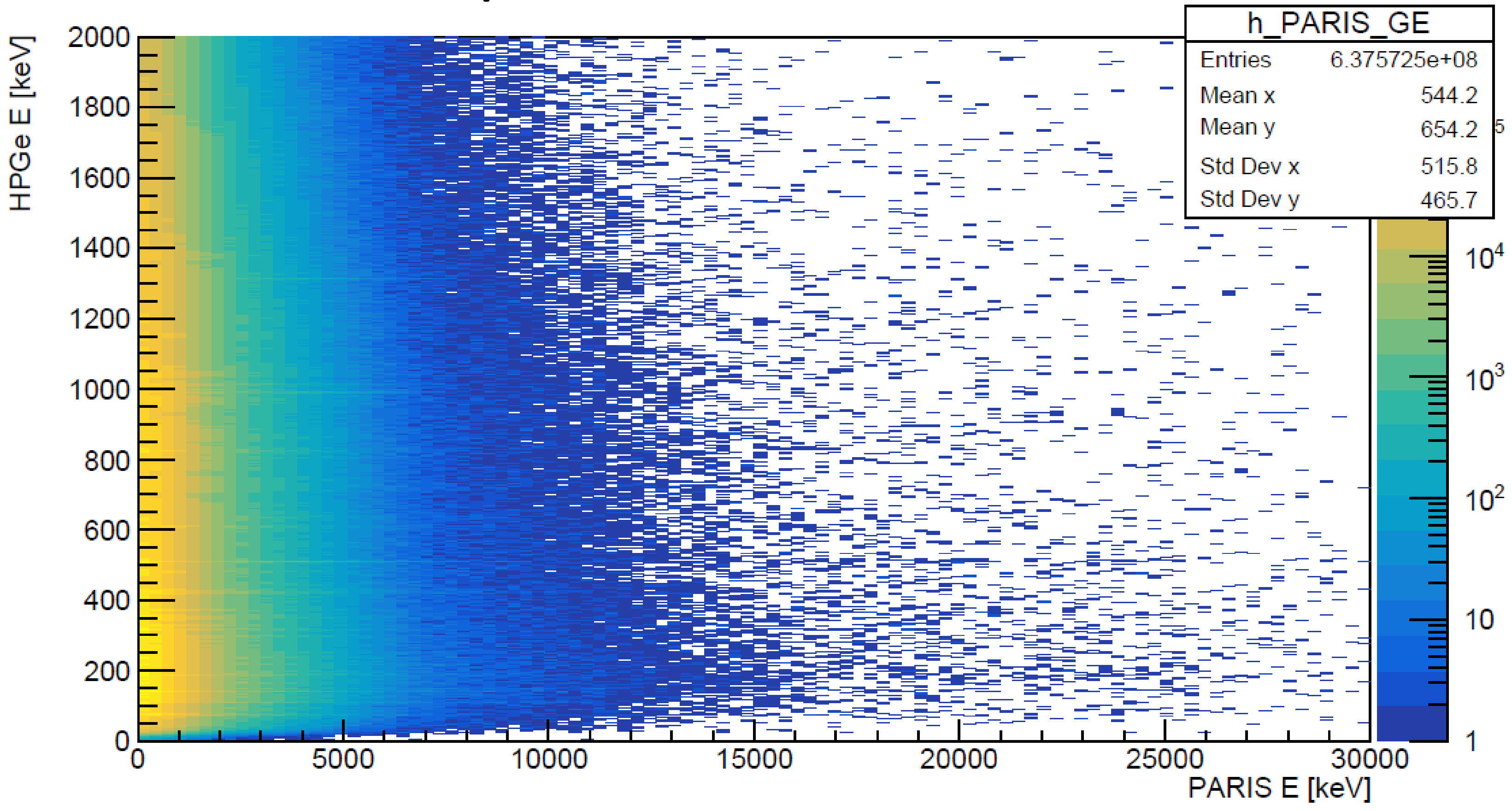
- **nu-Ball2 array**: Ge detectors around 90 degrees,
  ~4.5% efficiency at 1MeV (discrete $\gamma$ transitions)
- **2 × 36 PARIS phoswiches**:
  3% (at 23 cm) efficiency for 15 MeV $\gamma$ rays
  (high-energy $\gamma$ rays )

Event-by-event FOLD – (PARIS and nu-Ball2)

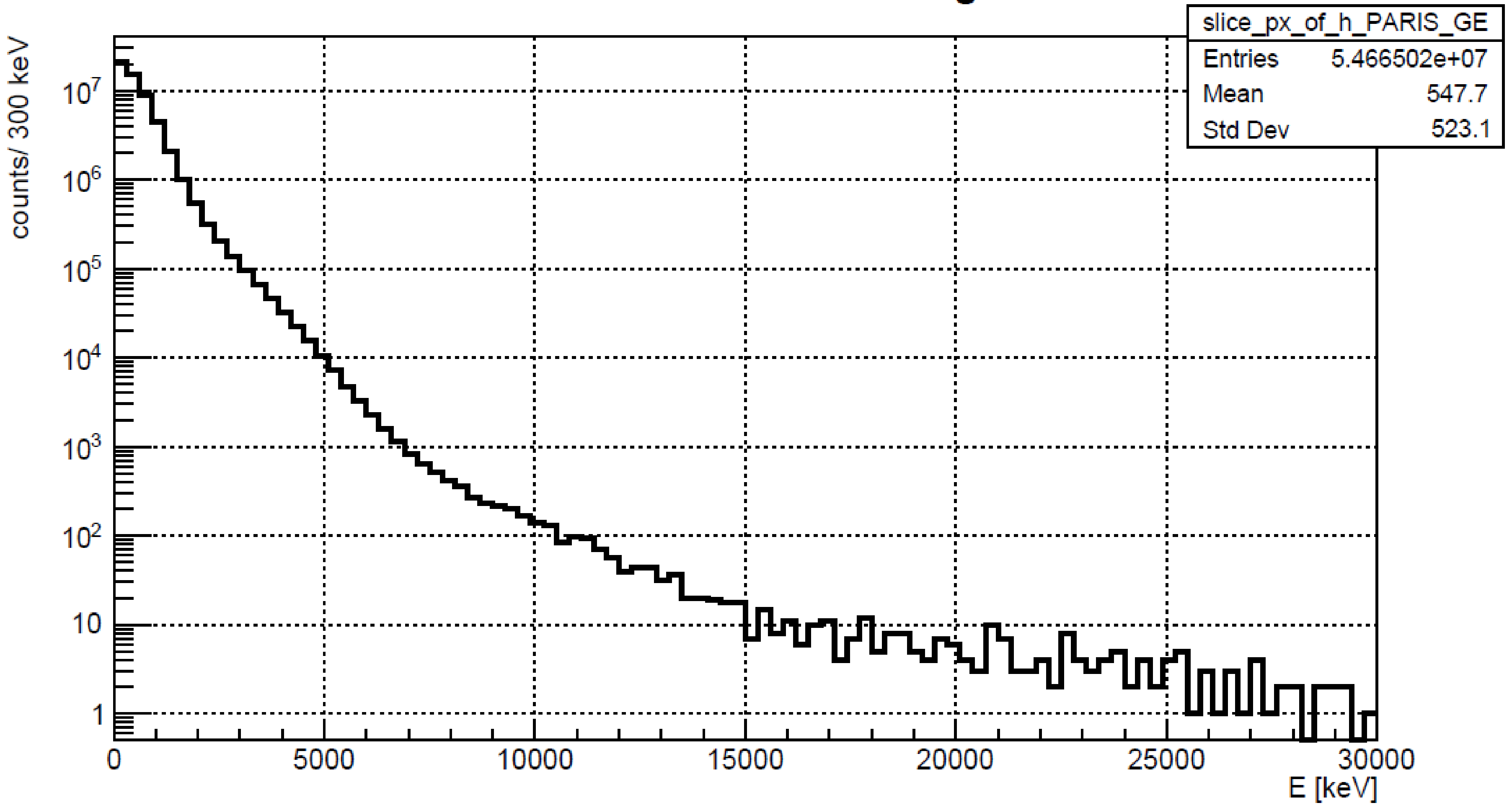
PARIS – two parts („walls")

**Analysis ongoing**

Prompt HPGe-PARIS matrix




**PARIS: 400 - 450 keV gated in HPGe**



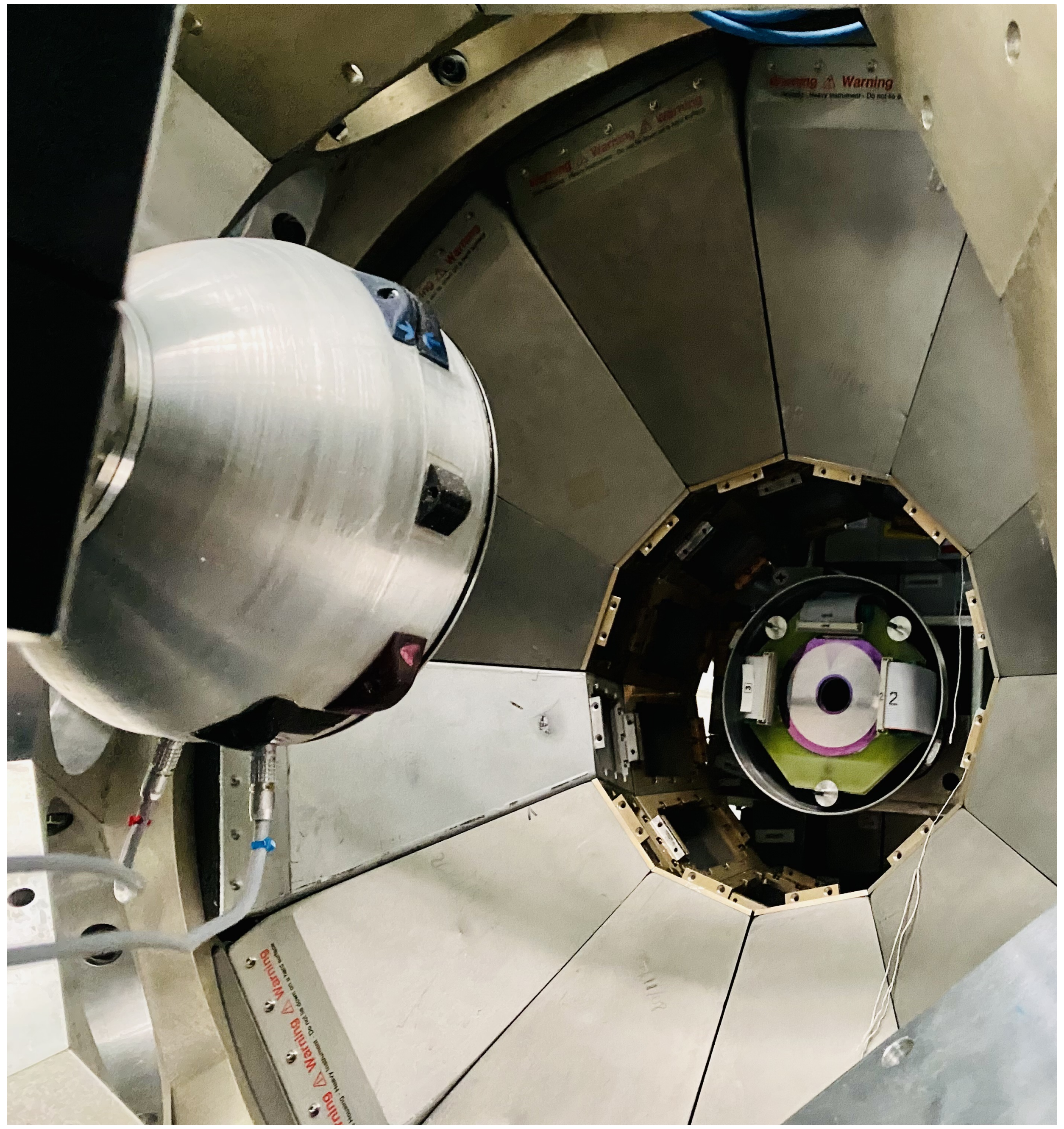
# Investigation of high spin structures in $^{44}Ti$ and $^{42}Ca$ via discrete and continuum gamma spectroscopy using NuBall2, PARIS, and Warsaw DSSD

**Experiment - N-SI-128**

Spokesperson: M. Matejska-Minda

**Performed June 2023**

**Set-up: Nu-Ball2 + PARIS + DSSD**



**Fusion-evaporation reaction: 110 MeV $^{24}Mg$+ 1mg/cm$^2$ $^{24}Mg$**

Gamma rays in coincidence with charged particles

# Investigation of high spin structures in $^{44}Ti$ and $^{42}Ca$ via discrete and continuum gamma spectroscopy using NuBall2, PARIS, and Warsaw DSSD

## Experiment - N-SI-128

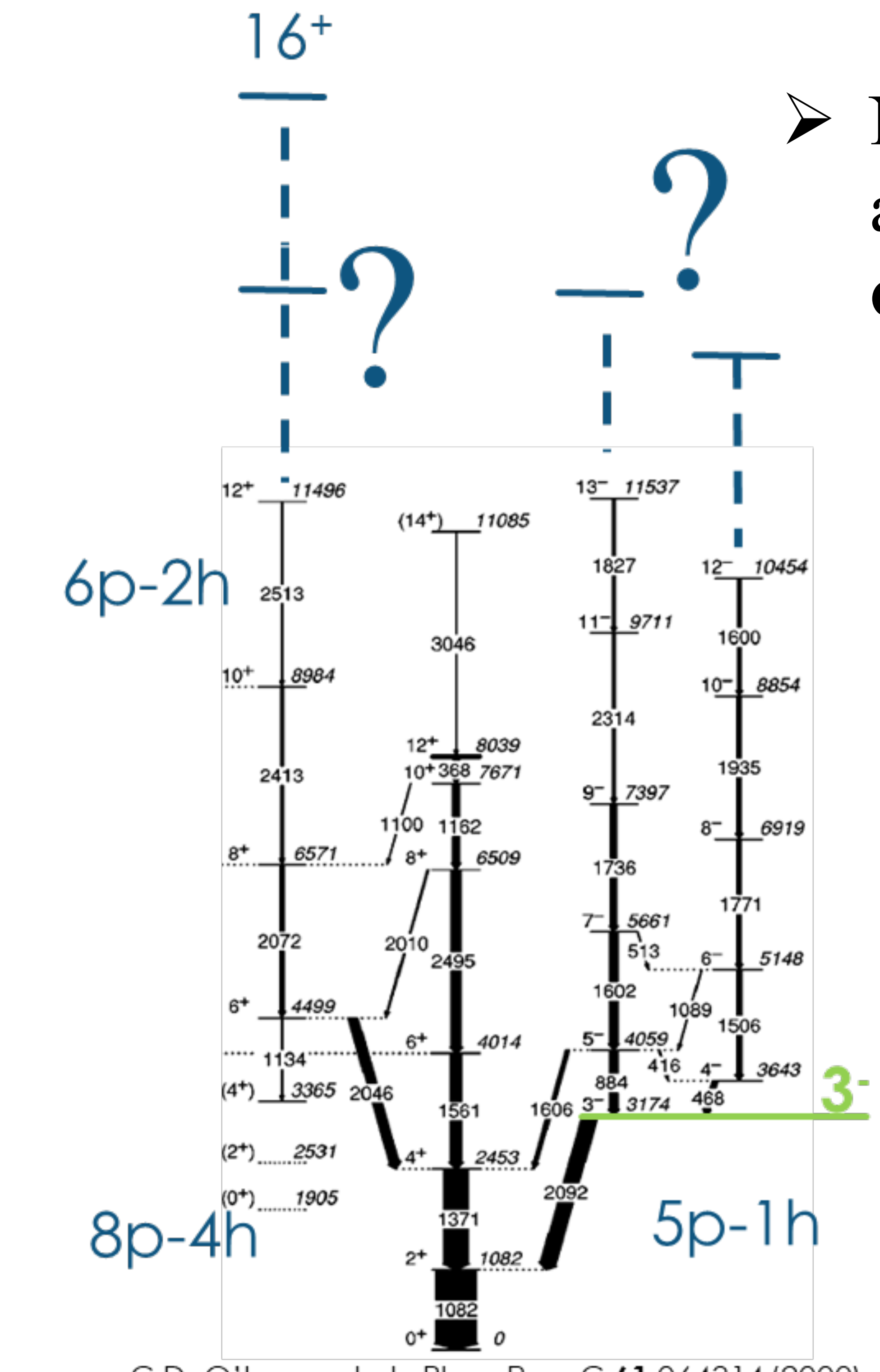
Spokesperson: M. Matejska-Minda

The aim of the measurement:

- Re-examine at high spins $^{42}Ca$ and $^{44}Ti$, in order to **extend the known and unknown structures** up to or beyond the terminating states.
- Investigating discrete and high energy gamma rays – link between deformed states (resonances) in a hot CN and yrast SD in a cold ER **by coincident measurement of continuum and discrete gamma-rays**.
- Expected results of this experiments will be helpful in the **evaluation of nuclear theories**, as well as testing the hypotheses of the new types of octupolarities predicted in these mass region.

## $^{46}$Ti

## $^{44}$Ti

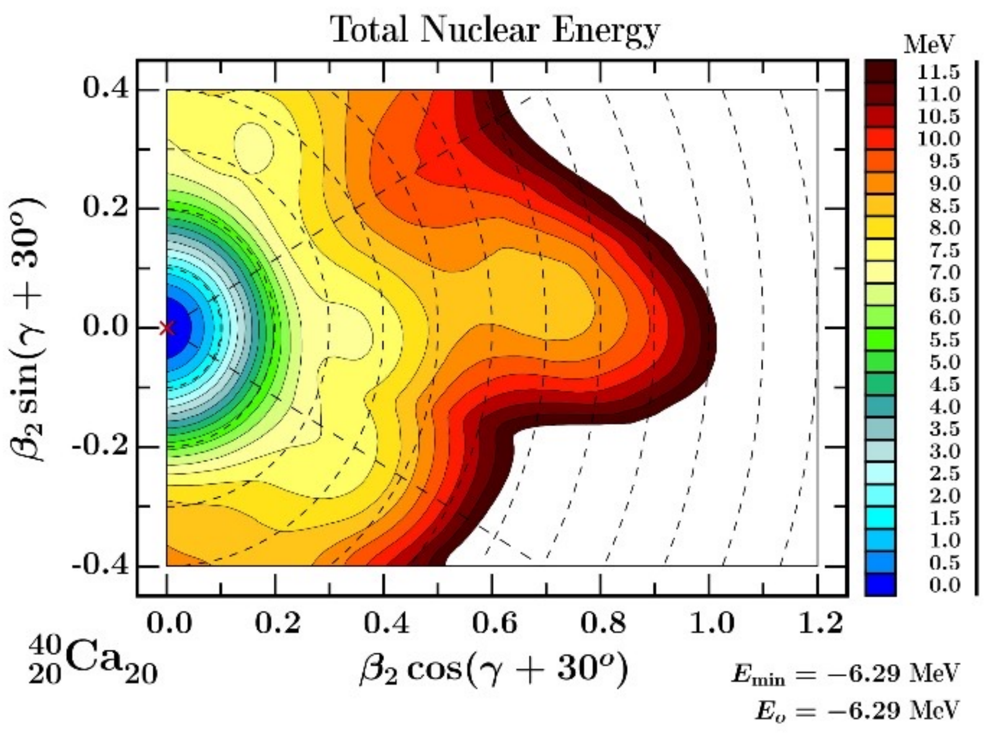


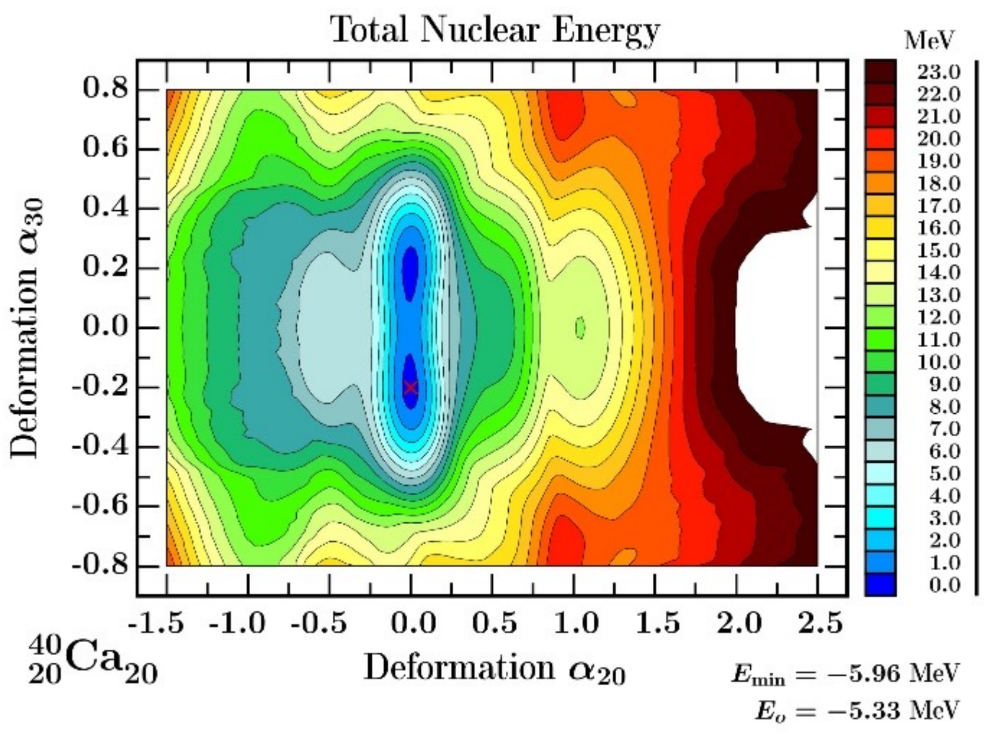

C.D. O'Leary et al., Phys. Rev. C **61**,064314 (2000).

- The positive parity excited band is interpreted as a SD band. It corresponds to a mixture of 8p-4h (beta~0.4) at low spins and 6p-2h (beta~0.3) at high spins, with $J_{max} = 16^{+}$, but this states were **not yet observed.**

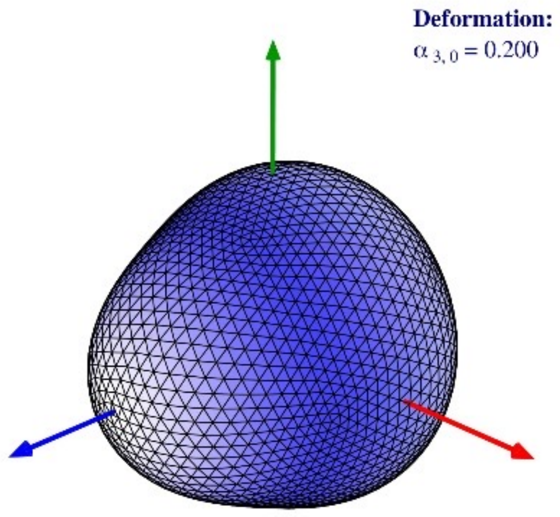
- Negative parity states form two rotational bands with a band-head at spin $J^{\pi} = 3^{-}$. Are interpreted as 5p-1h excitation and should arrive at the maximum aligned spin of $J_{max} = 15^{-}$ – **not yet observed**

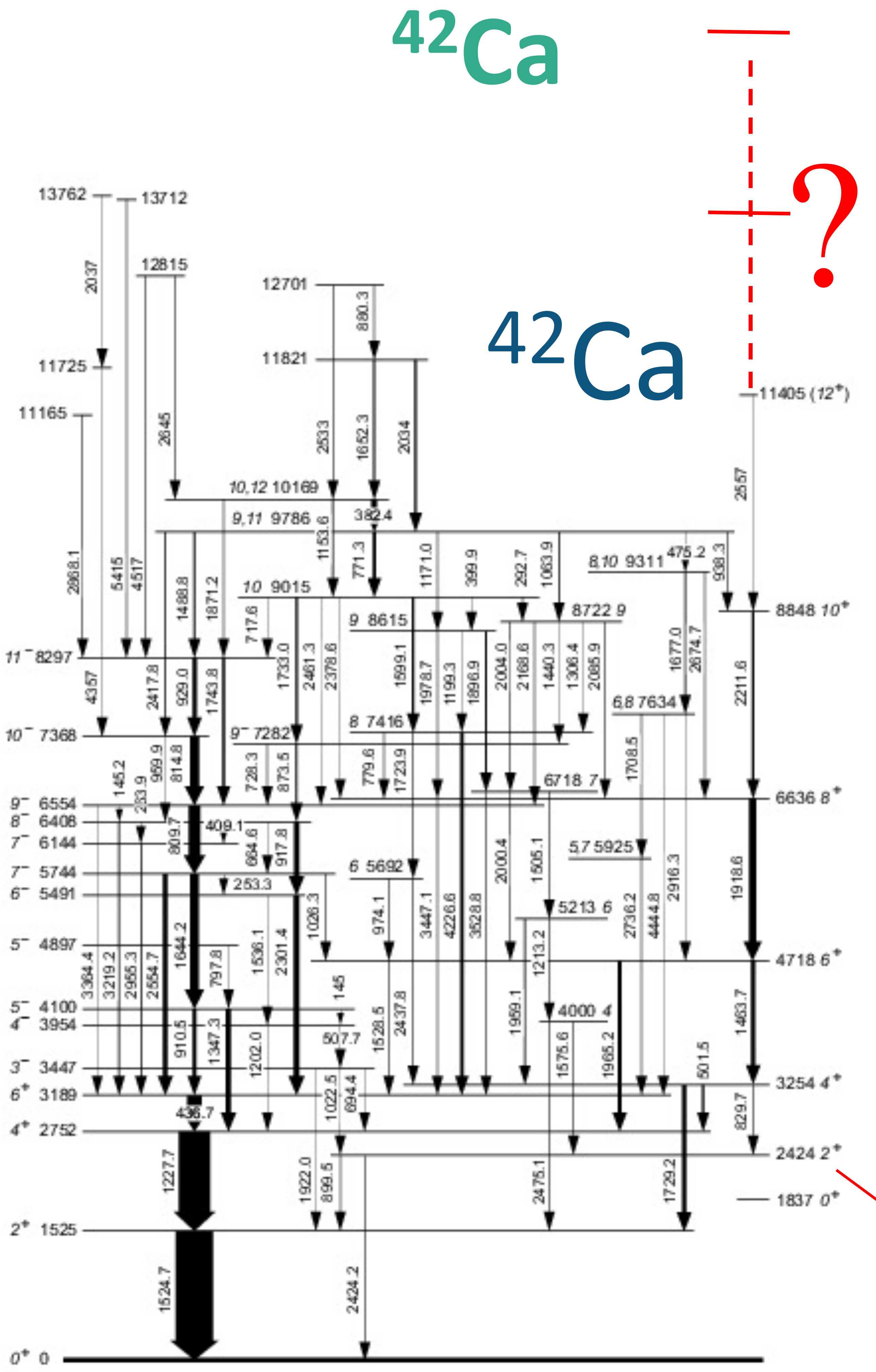
  - Mean-field calculations predict the presence of a new form of the nuclear octupolarity, which does not involve the quadrupole degrees of freedom, $\boldsymbol{\alpha_{20}} = \mathbf{0}$ with $\boldsymbol{\alpha_{30}} \neq \mathbf{0}$.
  - Such deformed ground state configuration could be a foundation for the excited negative parity structures, bulit on top of the $3^{-}$ state, in $^{44}$Ti



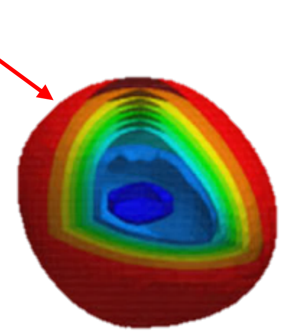




Shape corresponding to the octupole minimum






M. Lach et al., Eur Phys J. A **16**, 309 (2003).



$\beta_2$=0.43(4), $\gamma$=13(+5,−6)°

- Investigate 42Ca at high spins, to experimentally check if such a band continues beyond SM spin limit (as SD should behave) or just terminates.

# Experiment - N-SI-128 info

**Analysis ongoing**

- It was very challenging experiment due to the very difficult beam $^{24}Mg$ and different setup that originally planed
- Collected statistic (~**3 days** of 11 days granted) most probably is not sufficient to obtain all the proposed experimental goals
- For the strongest reaction channel like $^{41}Ca$ one can hope to obtain new results

| Nucleus | Channel | σ [mb] |
|---|---|---|
| $^{45}Ti$ | 2p1n | 55 |
| $^{44}Ti$ | 2p2n | 60 |
| $^{44}Sc$ | 3p1n | 140 |
| $^{42}Ca$ | α2p | 36 |
| $^{41}Ca$ | α2pn | 240 |
| $^{39}K$ | 2αp | 110 |
| $^{38}K$ | 2αpn | 58 |
| $^{38}Ar$ | 2α2p | 68 |
| $^{35}Cl$ | 3αp | 96 |

# Planned experiment with PARIS/KRATTA at CCB

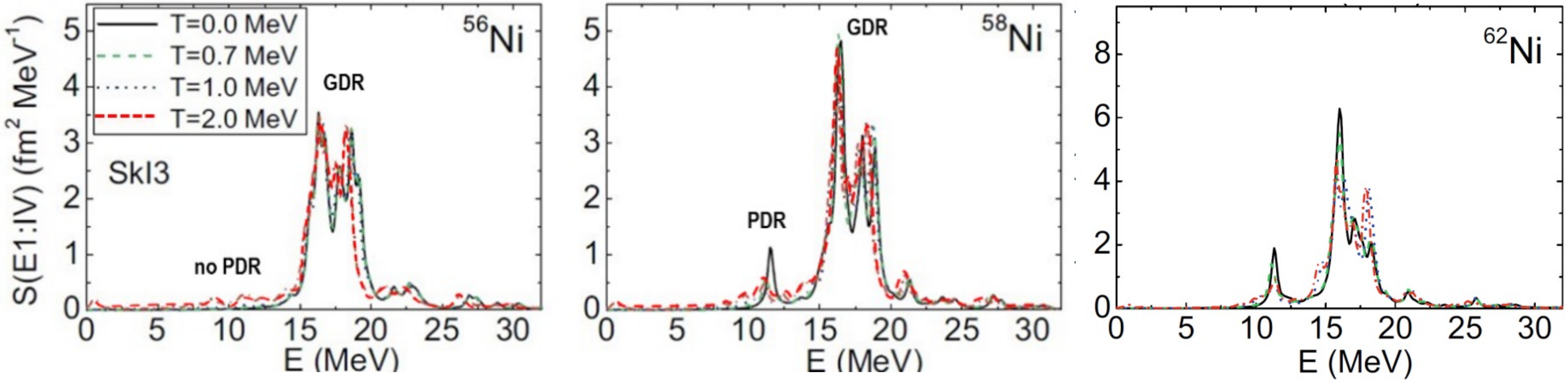
# The PDR states in $^{58,62}$Ni – at CCB IFJ PAN (2023/2024)

**Study:**

- PDR strength as a function of neutron number to understand the role of neutrons in states at the onset of the existence of the pygmy strength
- Comparison to the results of experiment performed recently at IFIN studying PDR in hot $^{56,62}$Ni isotopes

**Test run Dec 2023**
**Exp. Planned for 2024**

E. Yüksel et al., Eur. Phys. J. A (2019) 55: 230 and E. Yüksel private comm.




Theoretical prediction of the E1 strength in $^{56,58}$Ni and $^{62}$Ni, both for cold nuclei and at finite temperatures

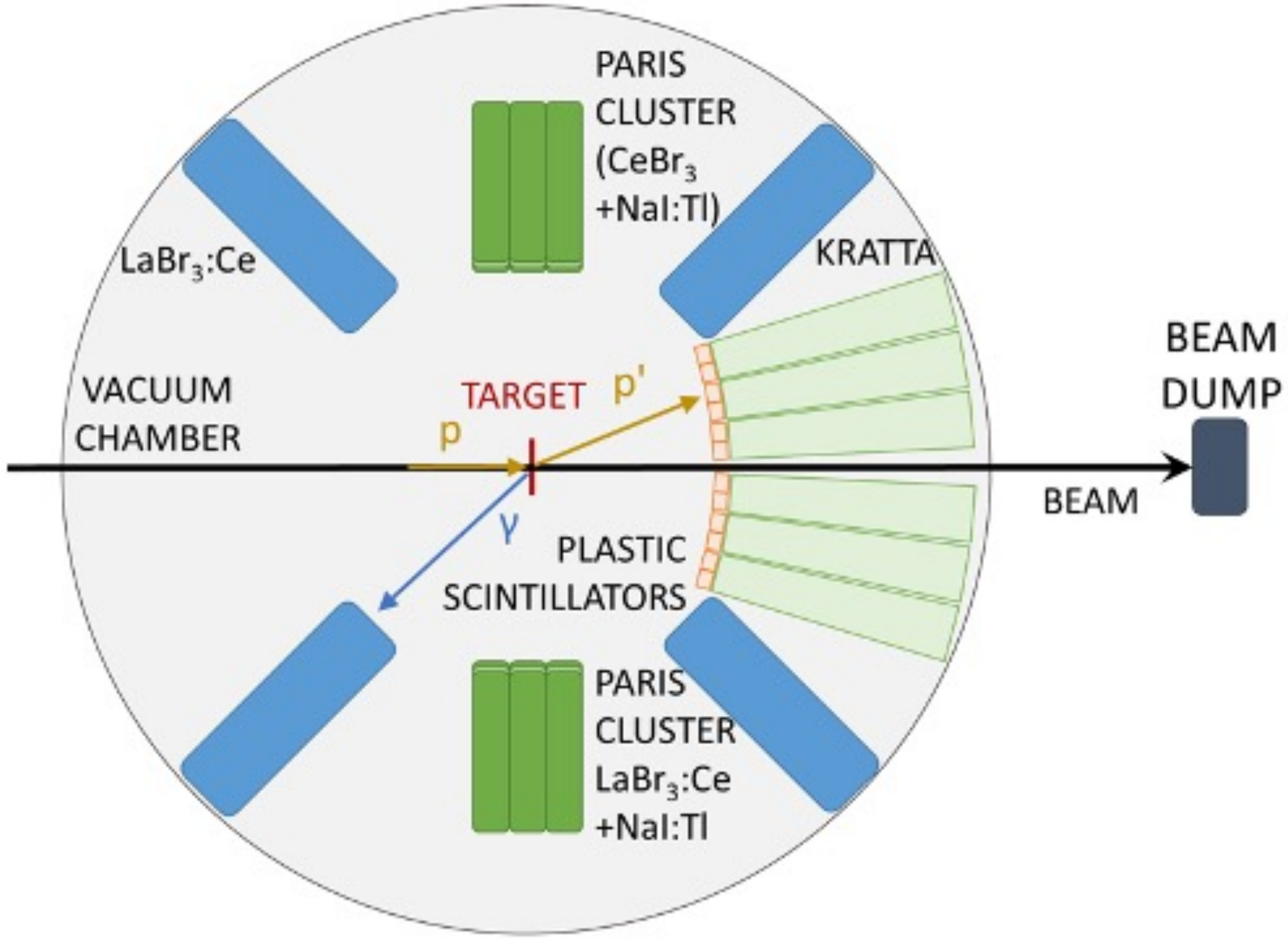
**(p, p'γ) experiment is extremely complementary and needed for analysis to one done at IFIN labs with same isotopes but with fusion evaporation reactions at finite temperature.**

# Planned CCB experiment

**Reaction: inelastic scattering of 180 MeV proton beam on $^{62}$Ni and $^{58}$Ni**

Beam: E=180 MeV and I= 0.4 nA

Targets: 50 mg/cm$^2$ of enriched $^{62}$Ni and, 100 mg/cm$^2$ $^{58}$Ni




**Experimental setup:** standard setup at CCB Krakow:

large scattering vacuum chamber

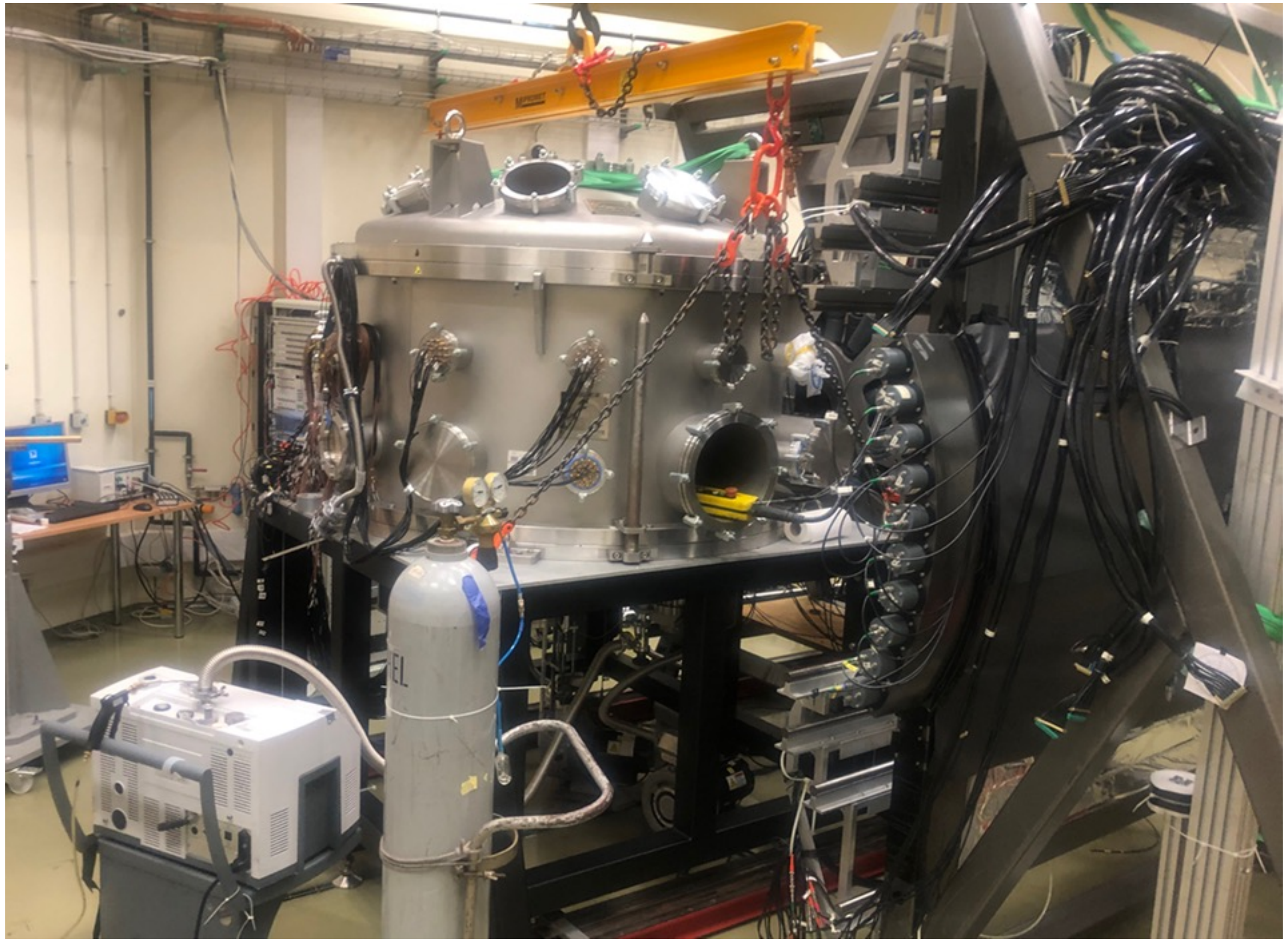
detectors:

- ❑ 32 **KRATTA** triple telescopes
  **measurement of the angle and energy of scattered protons**
- ❑ 4 large volume **$LaBr_3$** detectors (3.5”x8”) at top
- ❑ 2 **PARIS** clusters + 8 phoswiches (26 phoswiches)
  **measurement of the energy of $\gamma$ rays**

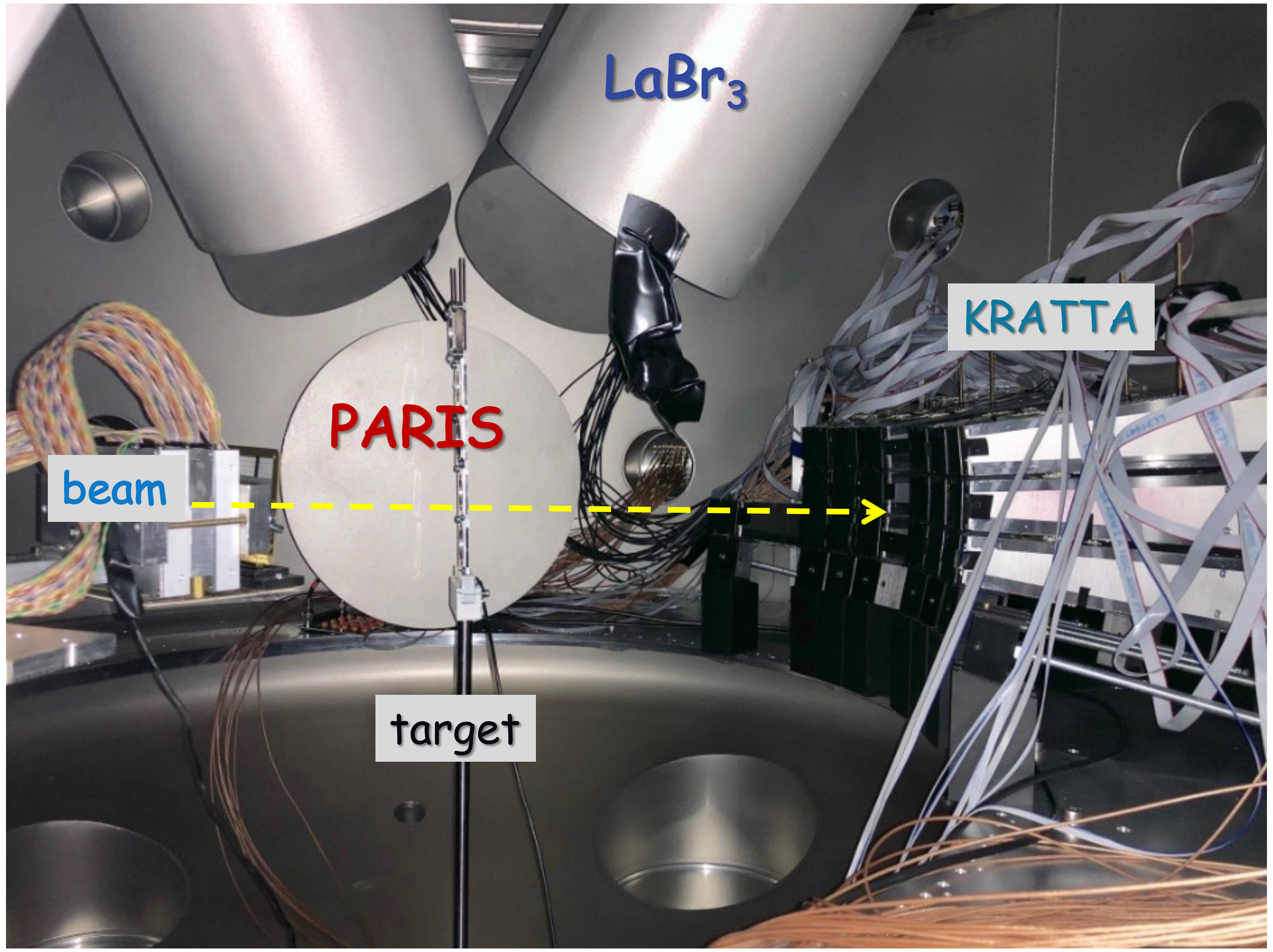
**Coincidence measurement of scattered protons and gamma rays**

# Preparing experimental setup

Scattering chamber



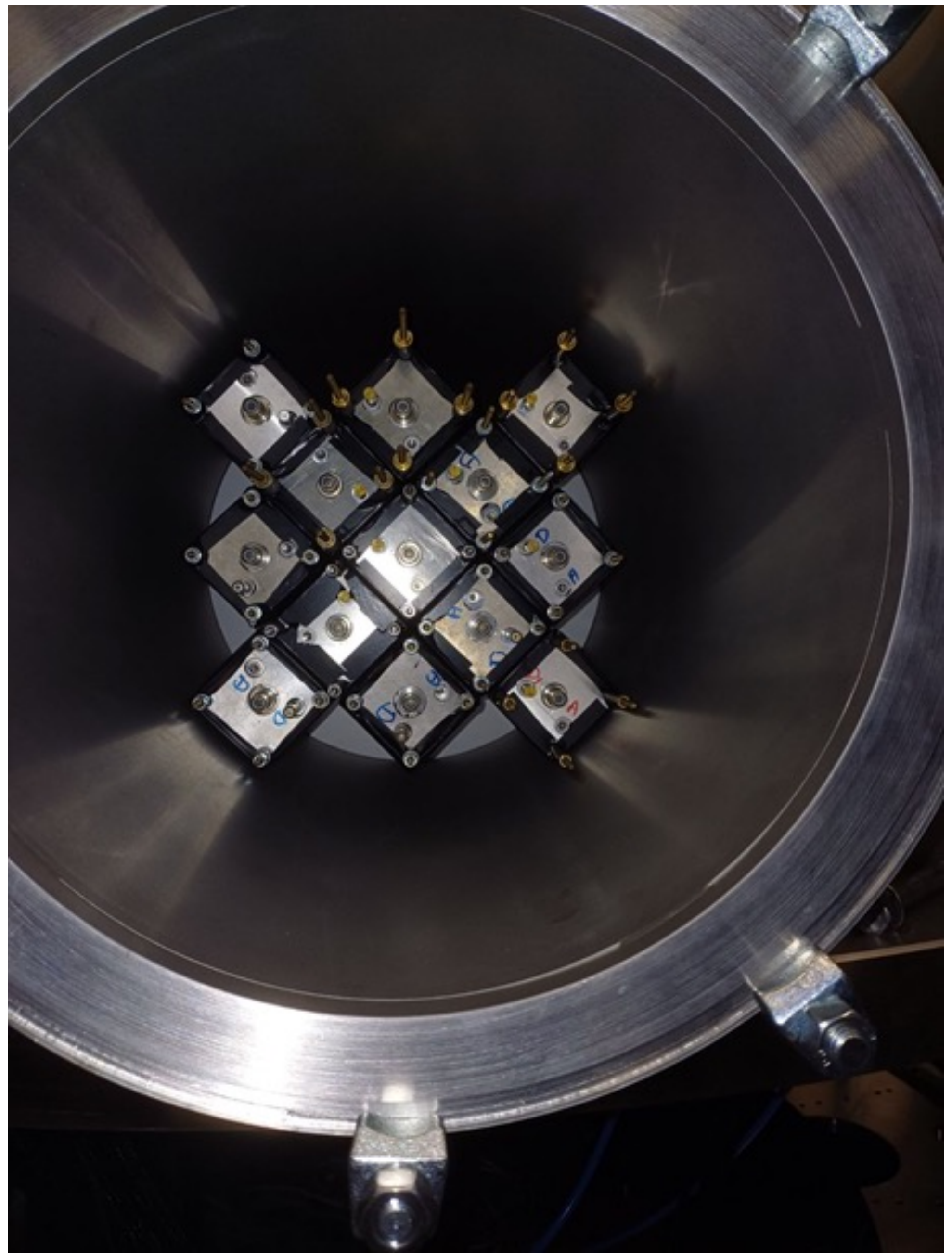
KRATTA inside the chamber – in the vacuum
γ detectors outside
mounted using holders / cylindrical pockets



# Mounting PARIS detectors

26 phoswiches (13 $LaBr_3$+NaI,
13 $CeBr_3$+NaI)

mounted in holders (at ~90°)

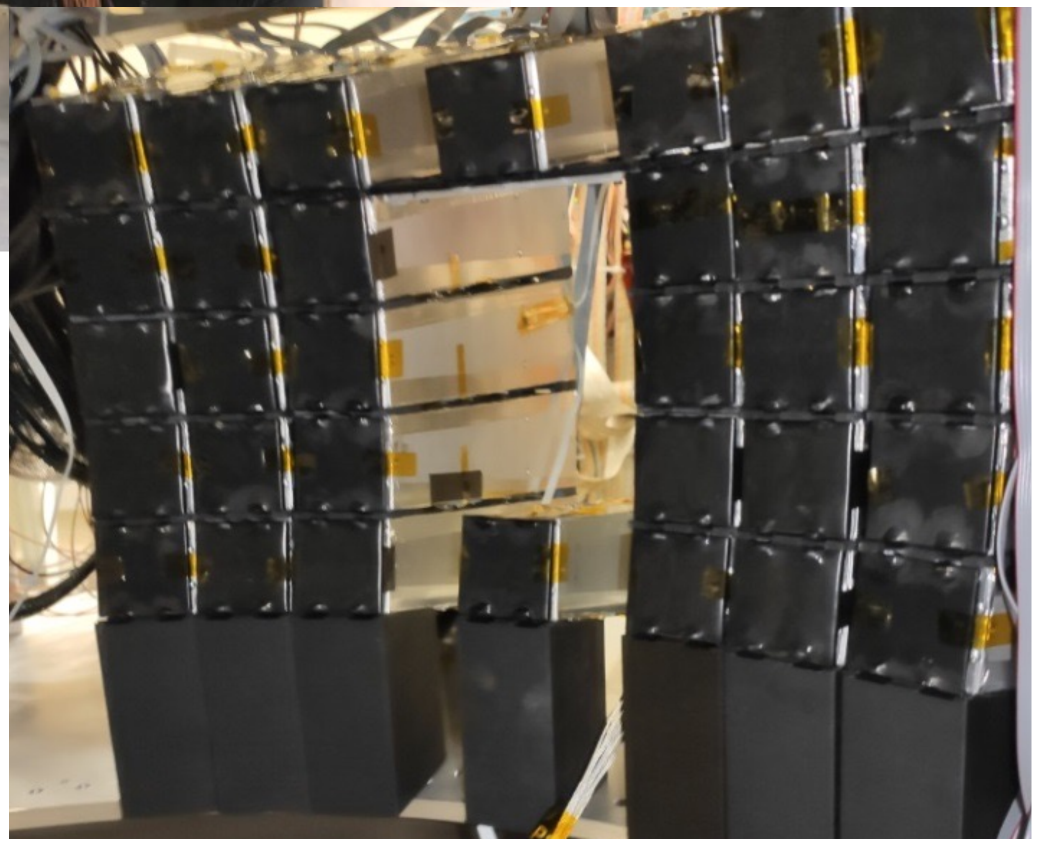


# Installing KRATTA detectors

32 tripple telescopes (Si + CsI + CsI)

(with segmented plastic scintillator in front for better time and angle resolution) mounted in 6 columns, each with 5 detectors, at the forward angles (from ~7° to ~23°)

**(~2 MeV energy resolution and 0.8° angular resolution)**



# Summary:

Recent experiments performed:

• Links between $^{80}Sr$ compound nucleus' shape and its residue's deformation studied with the GDR using NuBall2+PARIS – analysis is ongoing

• The investigation of high spin structures in $^{44}Ti$ and $^{42}Ca$ via discrete and continuum gamma spectroscopy using NuBall2, PARIS, and Warsaw DSSD – analysis is ongoing

Results obtained:

•The analysis of PARIS + NuBall experiment aiming to measure γ-decay of GDR from hot CN ($^{192}Pt$) in coincidence with discrete transitions from residues ($^{188}Pt$) showed similarity in the GDR gamma-ray energy spectrum, with gating on residue transition above (triaxial shape) and below isomer (near prolate shape). The better agreement to experimental data is obtained for the calculations assuming prolate-like shape of the nucleus. This might suggest either that shape of the nucleus is not always preserved during the decay, or wrong experimental assignment of the tri-axial deformation of the 12+ isomer.

Planned:

• Analysis of experiments performed at IJCLab (Nuball2 campaign) and CCB IFJ PAN (GQR gamma decay)

• New experiment in 2023/2024 at CCB: Study of Pygmy Dipole Resonances (PDR) in $^{58,62}Ni$, using inelastic proton scattering, at CCB IFJ PAN, Krakow, experiment during weekends (7 weekends)

• Participation in INTRANS Workshop (Jan. 2024 IJCLab, Orsay), data analysis meeting, and Zakopane Conference on Nuclear Physics (Aug. 2024 Zakopane, organized by IFJ PAN)

# The Collaboration

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